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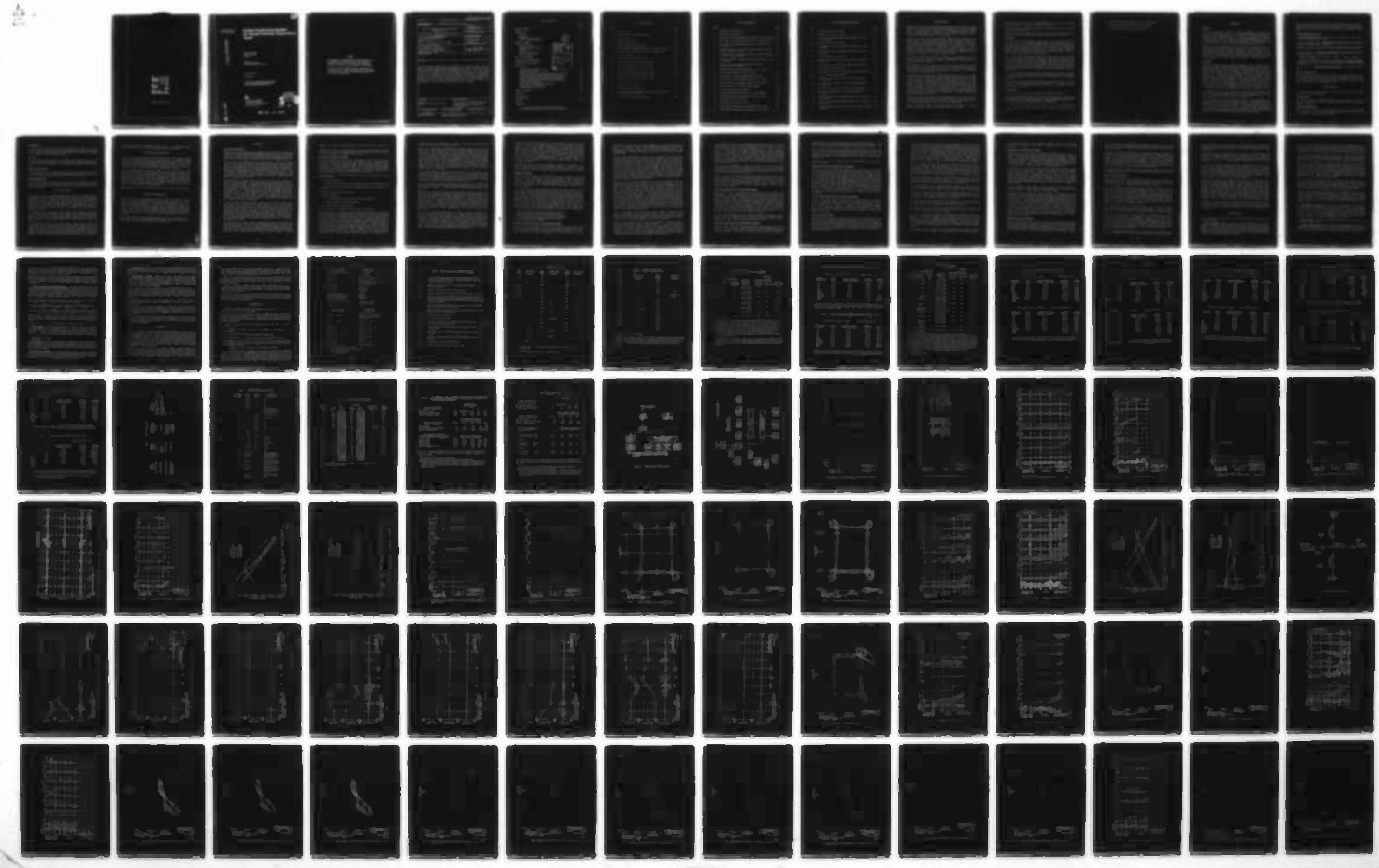

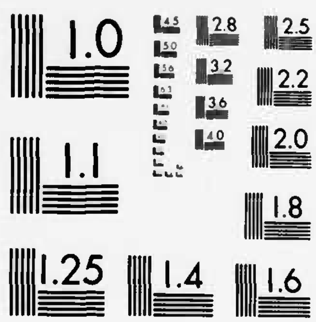
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Global Positioning System En Route/Terminal Exploratory Tests

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Final Report

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16. Abstract

The Federal Aviation Administration Technical Center performed this effort under the Technical Program Document 04-109, subprogram 049-311, project Navigation Satellite Timing and Ranging (NAVSTAR)/Global Positioning System (GPS). The report covers the exploratory laboratory test in 1981 and 33-hour flight test from June through July 1981 of the single channel GPS receiver (Z-set) manufactured by Magnavox and procured by the Department of Defense (DOD). The report documents the performance of the Z-set in the laboratory and during different flight profiles including rectangles, orbits, radials, nonprecision approaches, and area en route flights to the Philadelphia, Dulles, Norfolk, Wilmington, and John F. Kennedy Airports during periods when up to five satellites were visible to the antenna.

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EXECUTIVE SUMMARY

The Navigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System (GPS) is a satellite-based navigation and positioning system which provides extremely accurate position, velocity, and time information to suitably equipped users. A constellation of 21 (expandable to 24) satellites circling the earth in 12-hour, 26,000 kilometer orbits will be the source of the GPS navigation signals, and should be completely available in the late 1980's.

In 1981 the Federal Aviation Administration (FAA) conducted laboratory tests and 33 hours of fixed wing flight tests with a single channel GPS receiver, the Magnavox Z-set. This set sequentially processes coarse acquisition (C/A) signals on 1575.42 megahertz (MHz) from four satellites. The set selects the four satellites from those in view that are declared healthy in a message, called almanac, collected from the satellites. This almanac also contains data on all the satellite locations. The set uses these data to select the satellites that will provide the optimum positioning information from a geometric standpoint. The set will review periodically the satellite selected, and change satellites when a more geometrically suitable set of satellites becomes available.

The objective of the test was to gather information to help determine the eventual role of GPS in civil aviation by evaluating a single channel GPS receiver's performance in accuracy, reliability, integrity, responsiveness, and acquisition time in the laboratory and in-flight.

The laboratory tests were conducted at the FAA Technical Center with the GPS antenna located at a surveyed point on the roof of the Flight Operations Building. In the laboratory test, the system was monitoried to determine its performance in the absence of aircraft maneuvers. The system was also tested to see the effects of incorrect entry of position and time.

The flight test was conducted in a Grumman G-159 Gulfstream in June and July 1981, with the GPS single-channel Magnavox Z-set installed with instrumentation equipment in the cabin area. The aircraft was flown in various aircraft maneuvers and flight profiles including rectangles, orbits, constant bank turns up to 50° nonprecision approaches, and en route flights to Philadelphia, Wilmington, Dulles, Norfolk, and John F. Kennedy airports. The GPS system was connected to one of two antennas, the Microwave Specialty (top hat) antenna or a low cost Ball Brothers microstrip antenna, depending on the test being conducted. During flight, the Z-set was connected to a Hewlett-Packard System 1000 computer programmed to accept data from the Z-set and other airborne systems. The Nike-Hercules ground tracking radar data telemetered to the aircraft were recorded on airborne tape simultaneously with the other data.

Many of the terms used to describe the recommendations and conclusions of the testing have specific application and meaning to the GPS. These terms have been used and defined in other sections of this report and have been repeated here to facilitate an understanding of the conclusions and recommendations.

GDOP: The geometric dilution of precision reflects the influence of satellite geometry on the user's estimate of his position and his clock offset.

HDOP: The horizontal dilution of precision reflects the influence of satellite geometry on the user's estimate of his horizontal position.

C/A signals: GPS coarse acquisition signals on 1575.42 MHz are to be used by low cost civil aviation receivers.

Undegraded signal: An undegraded GPS signal is one that has not been adjusted/ modified to deny full accuracy to GPS users for national security reasons.

CONCLUSIONS.

1. A low cost properly designed GPS receiver which corrects observed problems with Z-set can easily meet the Federal Radionavigation Plan (FRP) requirements for en route, terminal, and nonprecision approach when operating with an undegraded C/A signal, four satellites, and an HDOP less than ten, or three satellites with continuous altitude input and a HDOP less than four (highest value of HDOP with three satellites available during test period). The FRP technical issues are discussed under the "Summary of Results" in the body of the report. Tables 8 and 19 provide supporting data for this conclusion.

2. A low cost properly designed GPS receiver which corrects observed problems with Z-set can easily meet the accuracy requirements of FAA Advisory Circular AC 90-45A for en route navigation and nonprecision approach when using four healthy satellites, an undegraded C/A signal, and a satellite constellation providing an HDOP less than ten, or three satellites with continuous altitude input and an HDOP less than four. Flight technical error, when using a GPS receiver, was not addressed during these tests, but will be addressed in the forthcoming General Aviation Test in November 1982. Table 8 and figure 13 provides supporting data for this conclusion.

3. The Z-set performed with significantly less accuracy when using an undegraded C/A signal and only three healthy satellites without continuous altitude input when the aircraft changed altitudes and the pilot did not manually enter new altitude information.

4. There is a potential problem with radiofrequency interference (RFI) if other systems emit RF signals above -95 decibels referenced to 1 milliwatt (dBm) in ±1 MHz of the GPS C/A center frequency (1575.42 MHz) in a region where aircraft will use GPS for navigation.

RECOMMENDATIONS.

1. Maintain strict control over RF emissions in the GPS frequency band.

2. Determine the extent of worldwide coverage for different values of HDOP (10, 15, 20, and above) and number of satellites required to obtain certain HDOP levels. Examine GPS receiver navigation degradation as different numbers of satellites fail for different geographic locations and phases of navigation.

3. Consider the following GPS receiver design features for all GPS receivers:

a. Automatic and periodic collection of the almanac and satellite health status.

b. Smooth transition when changing satellite configuration.

c. Deletion of calibration mode for airborne receivers.

d. Automatic initialization of the GPS receiver.

INTRODUCTION

OBJECTIVE.

The overall objective of the Federal Aviation Administration (FAA) Global Positioning System (GPS) Program is to define and determine the potential role of GPS as a civil navigation system. The objective of the Navigation Satellite Timing and Ranging (NAVSTAR)/GPS project is to gather information to help determine the eventual role of GPS in civil aviation by providing timely data to formulate the FAA decision on future navigational standards. The NAVSTAR/GPS project is designed as a series of tests to evaluate the applicability and suitability of GPS to meet the objectives of the July 1980 Federal Radionavigation Plan (FRP).

The objective of the NAVSTAR/GPS project from March 1981 to February 1982 was to evaluate GPS Z-set system performance including accuracy, reliability, integrity, responsiveness, acquisition time, and the effects of signal variations due to aircraft dynamics, weather, multipath, radiofrequency interference (RFI), satellite availability, and satellite geometry. Emphasis in the test was and, in future tests, will be directed toward evaluating the potential of GPS navigation for the single-piloted, low performance, general aviation class aircraft utilizing a low cost GPS receiver.

BACKGROUND.

The current worldwide civil short range air navigation system, very high frequency omnidirectional radar range (VOR)/distance measuring equipment (DME), transmits fixed radial course information from the VOR ground stations and responds to airborne interrogations from the DME station. The VOR/DME ground station provides readily usable aircraft navigation information of bearing and distance within its coverage area. However, not all geographic regions permit effective VOR/DME service. For long range navigation, aircraft utilize Loran, Omega very low frequency (VLF), and inertial navigation systems. Each system has its advantages and disadvantages. The NAVSTAR/GPS is a candidate replacement for the these systems. This satellite-based navigation and positioning system provides accurate position, velocity, and time information. When the GPS is fully operational, a receiver/processor will select signals from several satellites, decode and process those signals to determine three-dimensional user position in any weather, 24 hours a day, anywhere on or near the surface of the earth. Unlike the DME system, the system is totally passive and a high number of users will not saturate the system.

A complement of five satellites in two circular orbital planes presently permit three-dimensional, four-satellite navigation (4-hour interval when all satellites are in a healthy operational status) over selected geographical areas. Full operational capability is scheduled for the late 1980's.

The FAA implemented an extensive program in 1979 to define and determine the potential role of GPS as a civil navigation system. In preparation for the NAVSTAR/GPS project, the FAA requested early in 1981 that Magnovox incorporate the latest version of the software, version 10, in the Z-set and deliver the modified receiver to the Technical Center for test. The Technical Center interfaced both the laboratory and airborne data collection systems to the set and conducted exploratory flight and laboratory tests during 1981. The Technical Center flight tested the set in a Grumman G-159 Gulfstream during June and July 1981.

This report contains the test results in the Gulfstream aircraft and laboratory. General Aviation operational tests will be conducted in 1982. Pilots will navigate nonprecision approaches alternately by GPS and VOR in an Aero Commander, while a microprocessor system will record data for computation of pilot flight technical error.

RELATED DOCUMENTATION/PROJECTS.

1. Federal Radionavigation Plan, published by the Department of Defense and the Department of Transportation, July 1980.

2. Advisory Circular 90-45A, Approval of Area Navigation Systems for Use in the U.S. National Airspace System, February 1975.

3. Connor, Jerome T., Project Plan for NAVSTAR/GPS Fixed Wing Z-Set Testing, DOT/FAA/CT-81/20, March 1982.

4. Till, Robert D., Evaluation of NAVSTAR GPS as a Rotary Wing Navigation Aid Using Magnavox Z-Set, DOT/FAA/CT-81/60, April 1981.

5. Navigation Journal GPS, Special Issue, Volume 25, Number 2, Summer 1978.

6. Magnavox Government and Industrial Electronics Company, User's Manual (Computer Program) for User Equipment Z-Set of the NAVSTAR Global Positioning System, DCRL Item AOOX.

7. Luciani, V. J., NAFEC Range Instrumentation Systems, FAA-NA-79-32, February 1980.

CRITICAL TECHNICAL ISSUES.

The GPS Operational Test final report, scheduled in February 1983, will address GPS performance in relationship to all the critical and technical issues identified in the FRP, volume VI, page A6, for any candidate navigation systems. This report provides results of the laboratory tests in 1981 and early 1982, and the 33-hour flight tests from June through July 1981.

TECHNICAL APPROACH

The technical approach divided exploratory evaluation test of the Z-set covered by this report into six broad categories.

ACQUISITION TEST.

The test was conducted to determine the amount of time it takes for a Z-set to acquire the satellites and develop a usable navigation solution under different operation conditions.

LABORATORY MONITORING TEST.

The test monitored the Z-set position data output when the Z-set antenna is mounted at a survey point. The test was to determine the effect of satellite location, time, weather, etc., on the Z-set position data.

AIRBORNE TEST.

The test was conducted to determine the performance of the Z-set during various aircraft maneuvers and flight profiles including rectangles, orbits, constant bank turns, nonprecision approaches, and en route segments to Philadelphia, Wilmington, Dulles, Norfolk, and John F. Kennedy airports.

RFI TEST.

The laboratory RFI test monitored the GPS signal pulse (up-down) counters in the Z-set while injecting RFI signals in the antenna cable utilizing a hybrid coupler. The airborne RFI tests monitored the RF environment in and near the GPS frequency band.

ANTENNA EVALUATION TEST.

The test was conducted to determine if there were any noticeable effects on the Z-set performance if a low cost Ball Brother's microstrip antenna was substituted for the Microwave Specialty antenna that was delivered with the Z-set.

BLUNDER ANALYSIS TEST.

The test was conducted to determine the effect on Z-set performance if mistakes were made that could easily be made by an operator. These mistakes include operating the system in Cal mode when moving and entering erroneous input data while initializing.

TEST ITEM DESCRIPTION

The Magnavox Z-set is a single channel receiver which sequentially processes C/A signals on 1575.42 megahertz (MHz) from four satellites. It was designed as a relatively low cost, low dynamics, but fairly sophisticated first generation navigator for transport aircraft. The Z-set consists of the antenna assembly, low noise preamplifier, receiver/processor, and control display unit (CDU). Its main features are given in table 1. The CDU displays only one parameter (one line) at a time, but all of the CDU display parameters for a given time can be stored by activating the freeze button. The Z-set can accommodate only two-dimensional (horizontal) waypoints.

The FAA performed tests on a Z-set, serial number 6, with software version number 10. Within the Z-set the resident 8-state Kalman filter computes user position, velocity, time error, and frequency error normally every 1.2 seconds (the normal sequence time per satellite). The processor updates the CDU position display every second based on the last navigation solution for aircraft position, speed, and ground track.

The Z-set periodically reviews its stored satellite almanac data and determines the optimum satellite constellation and the time to change constellations. The algorithm for the latter function weighs the geometric dilution of precision (GDOP) value, satellite health status, tracking and data gathering history, and satellite visibility period. The satellite tracking program initiates track at a minimum elevation angle between 10° and 15° above the horizon. An interface module to the Z-set accepts encoded barometric altimeter data (increments of

100 feet/30.5 meters) for processor controlled input to the navigation solution during periods when only two or three healthy satellites are available.

LABORATORY TEST CONFIGURATION

The Z-set receiver, controlled by the CDU, connects to the Z-set interface module and to the laboratory automatic data collection system. The laboratory system consists of a Hewlett-Packard Computer System 1000, series 2100, model 45, with a 9-track tape recorder and a high speed printer/plotter (figure 1). The test team mounted the Z-set preamplifier and antenna at a surveyed position on the roof of the FAA Technical Center Flight Operations Building with an unobstructed view of the surrounding area and located about 75 feet from the Z-set receiver.

The Z-set monitored the GPS satellites signals from the surveyed position; the automatic data collection system recorded the Z-set navigation solution every 1.2 seconds. The test team activated the Z-set when two or three satellites were available; the set operated unattended throughout the time that at least four satellites were available. The receiver reverted back to the initialized state when less than two satellites were available or when the estimated position error (EPE) became large (EPE >20 nmi). This stopped the automatic data collection process. The test team also operated the Z-set with the CDU and inserted different values of position and time for blunder analysis.

Table 2 lists the major Z-set related parameters recorded during ground monitoring of the Z-set.

AIRBORNE TEST CONFIGURATION

The Z-set receiver and CDU provided data to the airborne data collection system which consisted of a Hewlett-Packard System 1000, series 2100, model 25, with a 9-track tape recorder (figure 2). The GPS antenna was mounted on top of the Grumman G-159 Gulfstream fuselage on the centerline near the leading edge of the wing. A 3-foot cable connected the antenna to the preamplifier in the aircraft cabin. Also connected to the data collection system via the position locating (PL) interface unit were the aircraft inertial navigation system, the radar range telemetry system, and the time code generator. A more detailed description of the interface unit and the list of parameters recorded during flight are contained in appendix A.

For several flights the team installed onboard the aircraft, independent of the above system, an RFI recording system (shown in figure 2) to record RFI measurements around the GPS C/A mode frequency of 1.5 gigahertz (GHz).

TEST RESULTS

ACQUISITION TEST RESULTS.

Acquisition time period begins with the completion of the initialization period and ends when the system illuminates the navigation light on the CDU. Initialization period is the entering into the CDU your position (latitude, longitude, and altitude in WGS-72 coordinates), relative movement (speed and direction on earth), and time (day of week in numerical code and time of day in Greenwich Mean Time).

After the system has progressed from the "initiate" mode, it enters the "standby" mode until the satellites' signals are acquired and the ephemeris data (accurate satellite orbit information) are collected from each satellite. The processor of the set then determines its position (within predetermined limits) before progressing to the navigation mode. The system estimates its position by looking at the variations in range measurements to the satellites and developes its EPE. If the EPE converges to less than 0.25 nmi, it alerts the pilot that the system is ready to be used for navigation. If the EPE diverges to greater than 20 nmi, the system reverts back to the initiate mode and waits for the pilot to again enter his position, relative motion, and time.

During the FAA test, the acquisition time varied from 3 to 14 minutes, depending in part on RF oscillator warmup. The average acquisition time was 6.4 minutes. A list of acquisition times, corresponding dates, and conditions relative to system behavior are shown in table 3. However, there were numerous times when the system would proceed to the standby mode, and after 1 to 3 minutes it would revert back to the initiate mode. For the most part, the situation was corrected by collecting a new almanac, which is a table describing the health and approximate path of each satellite in the sky. In the remaining times, the situation was corrected by repeated tries at acquisition until the system successfully acquired the satellites. A high satellite signal strength or an improper almanac from the satellites (problems have since been corrected by GPS ground control segment) may have caused the difficulty in acquisition.

It is necessary to manually instruct the Z-set to collect a new almanac periodically because the health and the approximate path of the satellites in the sky changes. The health of the satellites depend, in part, on the frequency standards (clocks) in the satellites. The satellites' signals are monitored by GPS ground monitoring stations. If a satellite clock drifts out of tolerance, it is either corrected or labelled unhealthy in the almanac by GPS master control at Vandenberg Air Force Base until the situation can be corrected. The satellites are moved from one orbital position to another as problems arise with different satellite signals, which also affects the accuracy of the almanac. If the almanac is not collected periodically, the system may be operating from time to time with a degraded satellite signal.

The amount of time it took to collect an almanac varied from 3 to 24 minutes with an average time of 8.4 minutes. This value is much less than that stated in the Z-set operators manual, i.e., that it takes approximately 20 minutes to collect an almanac. However, at the time we conducted our test only five satellites were operational. Only almanac data for these satellites were needed to be collected, which could reduce the amount of time it takes to collect an almanac. A list of

almanac collect times, corresponding dates, and related conditions are contained in table 4.

The system would hold the ephemeris data if the antenna was disconnected or if the power was interrupted for less than 1 minute. The system reacquires the satellites in 1 to 3 minutes when the ephemeris data are held.

LABORATORY MONITORING TEST RESULTS.

FAA personnel operated the GPS system in the laboratory with the antenna mounted at a survey point on the roof of the FAA Technical Center's Flight Operations Building. The laboratory automatic data collection system recorded the data from system activation to system shutdown. This data recording period normally started when two healthy satellites were above the horizon, continued through the period when four satellites were available, and automatically shutdown when the system reverted back to initialization state. This occurred when only one satellite remained in view or the Z-set EPE was 20 nmi or more.

The performance of the Z-set varied from day to day and is dependent, in part, on the following:

1. Operating mode selected.

   a. Navigation mode (position, relative motion, and time determined by Z-set).

   b. Calibration mode (ground speed and ground track set to zero internally in the Z-set).

2. Number of healthy satellites in view.

3. System configuration.

   a. With automatic digital altitude input (encoding altimeter).

   b. Without automatic ditigal altitude input.

4. Set of satellites selected by Z-set.

5. Age and accuracy of ephemeris data including clock parameters.

When the Z-set is not moving, as in our laboratory environment, it performs with less momentary variations (noise) in position in calibration mode than in navigation mode. When calibration mode is selected, ground speed and ground track are set to zero internally in the Z-set prior to the set determining its position. On April 25, 1981, the mean difference in horizontal position between the known location of antenna (antenna is located at a point surveyed to within 2 meters using signals from the U.S. Navy Navigation Satellite System) and the Z-set derived position was 12.1 meters for a 3-hour period. The system operated in calibration mode using signals and ephemeris data from four satellites, and satellite constellations providing HDOP from 1.8 to greater than 1300. The standard deviation for this period was 3.1 meters. Whereas, on May 5, 1981, the mean horizontal difference was 7.2 meters for a 3-hour period. The system operated in a navigation mode using signals and ephemeris data from four satellites. The

standard deviation for this period was 26.8 meters. The difference between the two modes can be readily seen from figures 3 and 4.

Figures 3 and 4 are plots of the means over every 30-second period for April 25 and May 5, 1981, respectively, of the difference in meters between the surveyed position and the Z-set derived position. The northerly difference in position is denoted by DX with a positive reading, indicating that the surveyed point is north of the Z-set reading. The easterly difference in position is denoted by DY with a positive reading, indicating that the surveyed point is east of the Z-set reading. The altitude difference in position is denoted by DZ with a positive reading, indicating that the survey point is higher than the Z-set reading. The 2D (horizontal difference and 3D (spacial difference) are the square root of the sum of squares of X and Y and X, Y, and Z, respectively. The dimensionless HDOP is computed from the ephemeris data collected from the satellites by the set, shown in figures 3 and 4. GS and GTK are also included in figures 3 and 4. GTN is the dotted portion of the bottom plot.

For a system not moving, the GS and GTK should be zero; when the system is in the calibration mode, these parameters are set to zero. In the navigation mode these parameters are determined by the Z-set and vary with each position fix of the Z-set. The ground speed varies between 0 and 2 knots, and the average is nearly 0.2 knots for a 30-second period when using four-satellite navigation. The ground track plotted is in degrees; ground speed is plotted in knots.

Table 5 is a summary of laboratory monitoring data of different test conditions and different HDOP for horizontal position means and standard deviation. Tables 6 and 7 are detailed summaries of supporting ground monitoring data for April 25 and May 5, 1981.

When the Z-set operated in NAV mode with five healthy satellites available on August 18, 1981, the mean and standard deviations for the period (HDOP was below 6.8) were 15.3 meters and 14.1 meters, respectively, for 8,750 data points. The Z-set changed satellite constellations from 8-6-4-9 to 8-5-4-9 to 8-5-4-6 to 9-5-4-6 to 9-5-4 and, finally, to 5-4 (numbers are the satellite pseudo random noise number codes). Figure 5 shows 30-second means of the parameters during this period. In figure 5 a change in satellite constellations is accompanied by a dip in HDOP value as the Z-set drops one satellite and replaces it with another. It can also be seen in this figure that there is no appreciable effect in changing satellites constellations except, occassionally, at the time of transfer for a minute or two.

The Z-set is not always transparent to a change in satellite constellations. This can best be seen in figure 6. Figure 6 is a successive difference plot of the change in position from one data point to the next (nominally 1.2 seconds per interval) for August 18, 1981 (same raw data as figure 5 but plotted as a first derivative on an expanded time scale). It shows an increase in the amount of position variation around the time the set selects a different constellation. This oscillation of position information would be disturbing to a pilot if the raw position data were used to drive course deviation indicator (CDI) needles during flight. However, systems could be designed to minimize this effect, or give the pilot control over when and what constellation would be selected.

On February 12, when the Z-set operated in NAV mode without digital altitude input and with only three healthy satellites in view, the Z-set performed as shown in figure 7. The mean and standard deviations are 13.2 meters and 49.0 meters, respectively, for the period shown. Positions of the satellites for February 23, 1982, are shown in figure 8 when the Z-set operated in NAV mode with digital altimeter input and with only three healthy satellites in view. The Z-set navigation performance is shown in figure 9. The mean and standard deviations are 18.9 meters and 10.0 meters, respectively, for the period 7:25 to 8:30 as shown in figure 9. As can be seen from comparing figures 7 and 9, the Z-set performs in a more stable manner with continuous altitude input. During the period prior to 7:25 in figure 9, there appeared to be GPS satellite system errors. These errors are being investigated.

The accuracy of any GPS receiver will depend, in part, on the accuracy of the ephemeris data that the set uses in determining its position. Detailed test on the effect of ephemeris data are not planned to be conducted until after the new GPS signal format and denial of accuracy provisions are implemented or resolved.

AIRBORNE TEST RESULTS.

The GPS system was operated in a Gulfstream aircraft for 33 hours in June and July 1981. The aircraft was flown in various aircraft maneuvers and flight profiles including rectangles, orbits, constant bank turns, nonprecision approaches, and en route flights to Philadelphia, Wilmington, Dulles, Norfolk, and John F. Kennedy Airports. The GPS system was connected to one of two antennas, a Microwave Specialty (top hat) or the Ball Brothers microstrip, depending on the test being conducted.

During local flights the ground Nike-Hercules Radar Tracking System, which consists of two radars, tracked a transponder on the aircraft. The aircraft position was derived from the radar which had the best signal-to-noise ratio at the time, and was telemetered to the aircraft and recorded on the GPS instrumentation system. During a portion of the turns, both the aircraft telemetry antenna and the radar transponder antenna were shielded from the ground antenna by the aircraft, which cause some gaps in the telemetry data. The existing radar accuracy is comparable to that of the Z-set and is not an order of magnitude more accurate than GPS. A detail description of the Radar Range Instrumentation system and its accuracy is provided in item 7 under "Related Documentation/Projects." The "Airborne Test Results" are divided into the following phases for convenience and clarity, were not conducted sequentially, and more than one profile was flown on some nights.

1. Rectangular Pattern Phase using four-satellite navigation.
2. Orbit Pattern Phase using four-satellite navigation.
3. Nonprecision Approach Phase using four-satellite navigation.
4. Constant Bank Turn Phase using four-satellite navigation.
5. Altitude Changing Phase using four-satellite navigation.
6. Three-Satellite Navigation Phase.

RECTANGULAR PATTERN PHASE USING FOUR-SATELLITE NAVIGATION.

On July 13, 1981, the FAA pilot flew the aircraft in four rectangular patterns with cloverleaf turns and bank angles up to 50°. The rectangular path is about 15 by 20 miles with about 20 percent of the time spent in turns with banks of 15° to 50°. Figure 10, an area plot, shows the flightpath of the aircraft on July 13, 1981, as

determined by radar; figure 11 shows the flightpath for the same flight as determined by GPS. Figure 12 shows the same flightpath as determined by both GPS and radar. As can be seen, there is very little difference between the radar and GPS determined flightpaths. They look like four paths instead of eight on this particular scale. To show greater position sensitivity, the following figures have been developed.

Figure 13 (same flight shown in figure 12) is a delta plot of the means over every 30-second period for July 13, 1981, of the difference in meters between the radar determined aircraft position and the Z-set derived position. The northerly difference in position is denoted by DX with a positive reading, indicating that the radar derived position is north of the Z-set reading. The easterly difference in position is denoted by DY with a positive reading, indicating that the radar derived aircraft position is east of the Z-set reading. The altitude difference in position is denoted by DZ with a positive reading, indicating that the radar derived aircraft position is higher than the Z-set reading. The 2D (horizontal difference) and 3D (spacial difference) are the square root of the sum of squares of X and Y and X, Y, and Z respectively. The HDOP (dimensionless) is computed from the ephemeris data gathered from the satellites by the set. The HDOP is shown in figure 13, which also includes the ground speed and ground track (ground track is the dotted portion of the bottom of the plot).

Figure 14 is a plot of the standard deviation for every 30-second period and corresponds with the periods in figure 13. Many of the parameters listed on figure 14 are the same. Altitude, coefficient of correlation between X and Y, and square root of GVAR (EPE with user clock offset uncertainity included) have been added to the graph. As can be seen from figure 14 and the ground track plot of figure 13, the standard deviation remained small throughout the flight, and only showed some activity during turns. The accuracy of the system is not greatly affected by HDOP for values below 10. The mean horizontal difference was 10.5 meters and the standard deviation was 25.5 between the Z-set and radar derived position. The Z-set was operating and using the ephemeris from four satellites, and the HDOP was between 1.8 and 10. These numbers do not include flight technical error (FTE) since the pilot was not flying GPS driven needles. It should be noted that the radar data are not smoothed or filtered, and wild point editing has not been employed. This will cause the mean and standard deviations of the difference between GPS and radar derived aircraft position to be higher. Plus, the accuracy of the radar is comparable to the GPS Z-set. Even so, the values of the mean and standard deviations are surprisingly low.

Table 8 is a summary of the flight data and shows the effect of HDOP on system accuracy for different nights as the HDOP increases. Tables 9 through 15 provide detailed flight statistics for various flights and are supporting data for table 8. The Z-set mean clock bias rate was 26.94 nanoseconds per second with a standard deviation of 10.8 nanoseconds measured over 2 hours and 21 minutes.

Figure 15 shows the position of the satellites during the test period; a plot of the satellites for HDOP of 10 is shown in figure 16. In a fully operational 21-satellite GPS system utilizing six orbits with 3 or 4 satellites per orbit in a nonuniform constellation, another satellite will appear prior to reaching an HDOP of 10, in most locations in the world, and the Z-set will select a new constellation. Further study could determine the amount of worldwide coverage available if HDOP of 10 or less were acceptable for navigation, and the amount of coverage that would be available if one or more satellites failed.

It is important to evaluate mean and standard deviations over 30-second intervals and much longer periods. It is equally important to observe the set from one reading to the next and the effects of maneuvers on the set. Figure 17 is a plot of the difference of the Z-set from one reading to the next for the flight on July 13. Z-set readings are normally 1.2 seconds apart. The radar data are plotted in the same manner. The variation between readings for radar is relatively small and does not indicate a need for filtering the data to obtain meaningful results. The variation between readings for GPS is relatively small during straight and level flights. The variation increases during turns and oscillates about the true position. The amplitude of low frequency oscillation (12 to 25 cycles per minute) varies with the rate of turn, and can increase to as much as 100 meters for a 50° bank turn.

After the turn was completed, the oscillations about the true position reduced exponentially and, essentially, disappeared in less than 1 minute. At 240 knots, the system would settle down in less than 4 nmi. The design of any guidance system using GPS must take into account these oscillations and the amount of time it takes to determine the navigation/position solution.

On July 6, 1981, the FAA pilot flew three rectangular patterns with similar results. Figure 18 is an area plot showing the GPS and radar derived path that the aircraft flew. Again, on this scale the GPS path falls so close to the radar path that it looks like three paths plotted instead of six. Figures 19 and 20 are the delta mean and sigma plots for July 6 and are similar in results to the previous plots of July 13, 1981. The value of mean and standard deviation for the flight are shown in table 10.

ORBIT PATTERN PHASE USING FOUR-SATELLITE NAVIGATION.

On July 8 and 9, 1981, the FAA pilot flew a 10-nmi orbit about the Atlantic City VORTAC station. Figures 21 and 22 are area plots showing the GPS and radar derived flightpaths. Once again, the GPS paths on this scale falls indistinguishly close to the radar derived paths. Figures 23 and 24 are delta mean plots of the difference of GPS and radar derived position for these flights and include several rectangular patterns, orbits, and nonprecision approaches for comparisons purposes. The orbit portion of the flight can easily be identified by looking at the ground track trace. The orbit took approximately 20 minutes to fly and was counterclockwise. The ground track trace on figures 2, 3, and 24 show a section where the ground track went from 359 to 0 over a 20-minute period, which is when the orbit was being flown. The HDOP reads zero when the system is operating with less than the signal and ephemeris from four satellites for these plots.

As can be seen from figures 23 and 24, there is virtually no difference in performance of the Z-set when flying the orbit than flying the rectangular pattern. The mean horizontal difference for the flights are 13.4 meters and 21.8 meters, respectively. Detail statistics are shown in tables 11 and 12.

NONPRECISION APPROACHES USING FOUR-SATELLITE NAVIGATION.

On June 26, 1981, an FAA pilot flew six nonprecision teardrop approaches to the FAA Technical Center's runway 13. The GPS and radar derived flightpath are shown in figure 25. The first plate shows the plots of GPS and radar determined nonprecision flightpaths. The second and third plates are the GPS and radar plots

shown separately. The remaining plates are the seven nonprecision approaches. The delta mean plot of the difference between GPS and radar is shown in figure 26. The mean and standard deviations are 3.7 meters and 17.4 meters, respectively.

On July 6, 1981, several nonprecision approaches were flown when the HDOP was very high. The GPS and radar derived flightpaths are shown in figure 27. The delta mean plot of the difference between GPS and radar is shown in figure 19. The approaches were conducted when the HDOP was between 4.3 and 159. The mean and standard deviations for the approaches were 8.1 meters and 117 meters, respectively.

In summary, there does not appear to be any unique problem with a teardrop non-precision approach.

CONSTANT BANK TURNS USING FOUR-SATELLITE NAVIGATION.

On July 15, 1981, an FAA pilot flew constant bank turns for two full revolutions (720°) with bank angles of 15°, 30°, and 50° when the HDOP was between 5.3 and 44. The GPS and radar derived flightpaths are shown in figure 28. The mean delta plot of the difference of GPS and radar derived positions is shown in figure 29. The successive difference between GPS readings and radar readings is shown in figure 30. As can be seen, the system estimated position error increased significantly during the high bank turns. The system alerted the operator that the information was questionable by lighting the standby light during a portion of the turn. The performance of the set during these maneuvers at HDOP levels of 25 was surprisingly good. During the 50° bank turns, each satellite was shielded by the aircraft fuselage during a portion of the turn since all satellite elevation angles were below 45°. Normally, when an emergency requires a pilot to make bank turns of 50° or more, a precise navigation solution is not required or used. The mean and standard deviations for this period were 51.1 meters and 121.9 meters, respectively.

ALTITUDE CHANGING PHASE USING FOUR-SATELLITE NAVIGATION.

On June 24 and July 13, 1981, an FAA pilot flew rectangular patterns at different altitudes, approximately 8,000 and 11,000 feet. There was no noticeable difference in Z-set performance at either altitude or when changing altitudes, as can be seen in figures 13, 14, 31, and 32. In general, the altitude parameter appears two to three times more sensitive to acceleration then changes in horizontal positions, especially during turns, as can be seen from figures 17 and 30. This apparent sensitivity to altitude may be caused by the geometry of the satellite constellation selected.

THREE-SATELLITE NAVIGATION.

In normal operations with four satellites, the Z-set uses the measurements to the four satellites to determine its spacial position (X, Y, and Z) and clock bias. When operating with only three healthy satellites available, the Z-set can determine its position using the measurement to three satellites and its last remembered altitude (altitude hold feature), or it can determine its horizontal position and clock bias by using three satellites and an altitude input. In either case, navigation with three satellites presents a different situation and is addressed in the following paragraphs.

On July 3, 1981, an FAA pilot flew the Z-set equipped Gulfstream utilizing the GPS signals and ephemeris from three satellites with digital altitude input. A plot of the mean and standard deviations of the difference between GPS and radar derived position are shown in figures 33 and 34. The accuracy of the system when operating with three satellites and digital altitude input is less than that of four satellites, as can be seen by comparing figures 13 and 33. The mean and standard deviations for the July 3, 1981, flight was 12.1 meters and 45.9 meters, respectively. The mean and standard deviations for the July 13 flight for a comparable 2-hour period with four satellites were 10.5 meters and 25.5 meters, respectively. On July 3 the HDOP, not shown in figure 33, varied from 1.8 to 3.0 and was computed by assuming a fourth satellite at the center of the earth to represent the altimeter.

On July 14, 1981, an FAA pilot flew the Z-set equipped Gulfstream utilizing the GPS signals and ephemeris from three satellites. During this flight the digital altimeter was connected to the Z-set for various periods of time. Manual altitude was inserted at different times during the flight to determine how the set reacted to these inputs. Figures 35 and 36 are the mean and standard deviation plots of the difference between GPS and radar determined position. The numbers 1 through 6 marked in the HDOP area of figure 35 are explained in the following paragraphs.

The period designated No. 1 is when the Z-set was operating using three satellites and was not connected to the digital altimeter. The Z-set EPE value was above 900 meters during this period and the absolute value of northerly (DX) and easterly (DY) difference between GPS and radar were greater than 1,000 meters.

The period designated No. 2 is when the digital altimeter was connected and the Z-set EPE almost went to zero immediately. The northerly, easterly, and altitude position differences reduced quickly to below 100 meters before the period ended.

The digital altimeter was disconnected for the period designated No. 3 when the aircraft was descending for an approach. The EPE increased gradually and continually. The northerly (DX) and altitude (DZ) differences increased continuously to more than 800 and 3,300 meters, respectively.

The digital altimeter was connected for the fourth period and Z-set performance improved immensely. The EPE, once again, went almost to zero immediately. The DX and DY values went almost to zero, and DZ went below 100 meters.

The digital altimeter was again disconnected for the fifth period which was flown at constant altitude, and the EPE, as before, gradually increased. However, DX, DY, and DZ did not increase as rapidly as before.

For the sixth period several nonprecision approaches with changing altitudes were flown. The altitude was manually inserted five times via the CDU and the EPE responded. The altitude determined by the radar was the value used to enter manually in the Z-set. The Z-set accepted the value the first time and corrected its altitude, but, at the same time, DX and DY increased in error. After repeated entries of manual altitude via the CDU, the Z-set apparently ignored the input. DX, DY, and DZ increased considerably, however, the EPE remained small throughout the period.

For the seventh and last period the digital altimeter was connected again and DX, DY, and DZ slowly reduced to their normal small values within 5 minutes.

In summary, the digital altitude input was extremely beneficial in determining position when navigating on three satellites, especially when a change in altitude took place.

RADIOFREQUENCY INTERFERENCE TEST RESULTS.

During several en route flights, RFI measurements about the GPS C/A center frequency were monitored with a spectrum analyzer and recording equipment, as shown in figure 2. The data from flights to John F. Kennedy, Philadelphia, Wilmington, Dulles, and Norfolk airports showed ambient RFI levels at approximately -115 dBm at the antenna terminals for a 300 kilohertz (kHz) bandwidth and random noise peaks at approximately -100 dBm. (All power level computations assume a preamplifier gain of 30 dB and ideal, lossless, isotropic transmitting/receiving antennas in free space and within line of sight, and are given at antenna terminals.)

In laboratory tests, the Z-set navigation solution exhibited catastrophic degradation within several seconds from -95 dBm continuous wave (CW) interference signal within ±1 MHz of GPS C/A center frequency of 1575.42 MHz. Under such circumstances, the stationary Z-set indicated speeds of 200 knots and its derived position diverged from the surveyed antenna position by 2,000 feet or more. During this period there was not an immediate corresponding jump in EPE, which normally indicates erroneous performance during an in-flight situation. Interference signals several dB higher causes rapid loss of satellite track. The aforementi ned spurious emissions (-100 dBm) observed during the flight program did not appear to affect the Z-set.

For CW interference signals within ±5 MHz of the GPS C/A center frequency but outside of ±1 MHz of center frequency, Z-set degradation begins at approximately -60 dBm. Table 16 is a summary table of the RFI observations.

A potential problem may develop if RF emission systems operate or have RF spurious transmissions at or near the GPS C/A center frequency. For instance, the third harmonic of the visual power from an ultra-high frequency television station, such as channel 23, is 1575.75 MHz, which is 0.33 MHz away from 1575.42 MHz (GPS C/A center frequency). The Federal Communication Commission (FCC) regulations limit the effective radiated visual power to 5 megawatts (97 dBm) and specify that the harmonics and spurious emissions must be attenuated no less than 60 dB below the visual power. For such a case, the Z-set would be affected by the signal if the aircraft with Z-set was within 35 nmi of the tower, assuming line-of-sight transmission between transmitting and receiving antenna. In practice, attentuations of 80 dB or greater are attained, and a Z-set receiver would not experience difficulties unless it was within 3.5 nmi of the transmitting tower. Care must be taken to protect the GPS frequency band from other operating systems by strict regulation and enforcement.

ANTENNA EVALUATION TEST RESULTS.

Two GPS antennas were utilized during the flight test. A Microwave Specialty antenna was supplied with the Z-set; a low cost Ball Brothers microstrip antenna was provided by separate contract. Both antennas were alternated on June 26. Seven nonprecision teardrop approaches were made between 11:15 p.m. and 12:50 a.m. The Microwave Specialty antenna was used for the first two approaches, the microstrip antenna was used for the next two approaches, and the Microwave Specialty

antenna was used for the remaining three approaches. Figure 37 is a mean delta plot of the difference between GPS and radar derived position during the period when the nonprecision approaches were made. There is no noticeable effect in the change of antennas.

On January 15, 1982, ground test on the unprotected Ball Brothers antenna was conducted. The antenna was mounted on the FAA Flight Operations Building in subfreezing weather and sprayed with water until 1/4 inch of ice built-up on the antenna. The system did not appear to be affected by the layer of ice, as can be detected by the delta mean plot shown in figure 38. The breaks in the data were caused by turning the Z-set off and reacquiring. The system acquired the satellites in approximately 6 minutes, which is normal. In the latter part of the monitoring period after 11:50 a.m., the Z-set was operating on three satellites without digital altitude input and the errors increased slightly.

In summary, there did not appear to be any Z-set performance difference between the two antennas. The Ball Brothers microstrip antenna was not affected by the severe ice coating placed on it.

BLUNDER ANALYSIS TEST RESULTS.

Project personnel conducted tests to determine the effect on the Z-set performance if mistakes that could easily be made by an operator were actually made. The intentional mistakes made and their effect are shown in table 17 and discussed in the following paragraphs. Supporting data are provided in table 18.

The Z-set operators purposely entered incorrect position information into the Z-set via the CDU during the data entering mode of the Z-set. The system is not sensitive to incorrect initial position information and can tolerate errors of 100,000 feet in altitude and 500 nmi or greater in horizontal location. For example, test personnel entered into the Z-set the latitude/longitude coordinates for Chicago, Illinois (approximately 750 miles away), Detroit, Michigan (approximately 500 miles away), and Jacksonville, Florida (approximately 800 miles away), when they were physically located with the set at the FAA Technical Center, Atlantic City Airport, New Jersey. The set acquired satellites without any problems and gave the correct position information.

At the FAA Technical Center's location, the Z-set will not acquire satellites when south (S) is inserted for north (N) during entry of the latitude data. The set would revert back and have to be initialized again. A similar situation occurs when east (E) is inserted for West (W) during entry of longitude data.

The set is critical to incorrect entry of time. If the wrong day is entered, the set will not acquire. If the right day is entered but time of day is incorrect, the set's behavior is unpredictable. Somedays it would accept errors of 1 hour or more and still acquire the satellites and display the correct time. Other days it would just correct the time and required the operator to reinitialize it. On still other days, it had to be initialized without correcting the time or giving the operator any clue as to why it failed to acquire the satellites. This is not a serious problem and does not involve safety of flight. Equipment can be designed to eliminate this shortcoming.

The other common mistakes with the Z-set are to fly with the system in calibration mode or in "standby" mode because the lights monitoring those functions are not

that pronounced and are easily overlooked. Flying with the set in standby mode most of the time is not that serious and the set quickly converges to the actual aircraft position within several minutes. It is similar to activating the system while airborne.

When the pilot makes the mistake of flying the system in calibration mode, the system derived position jumps erratically. Figure 41 shows the variations in successive Z-set position determinations. Even though the variations are high, the EPE values are relatively low and the navigation status light indicates acceptable performance. This can be corrected with minor system software changes, if deemed necessary.

There are other times the Z-set gets confused for extended periods of time (1 hour or more) in a 4:3 status, meaning that it is receiving data from four satellites and has collected ephemeris from only three satellites. In this case, the position error can almost be anything, as shown in figures 39 and 40, but the set's EPE is high and is the reason the standby light is illuminated to alert the pilot of the situation. In a rare conceivable instance, where it could be encountered in flight after a change in receiver selected satellite configuration, a properly designed GPS system would alert the pilot of its improper operation.

The problems discovered during these blunder analysis tests mainly involve an increase in aquisition time or failure to acquire and are a considerable inconvenience to pilots and airport personnel. These problems, once identified, are easily circumvented by equipment design. Ways to circumvent these system shortcomings are to improve equipment status lights, incorporate a continuous battery operated clock to maintain accurate time when system power is disconnected, and an automatic almanac collection feature. The need for a calibration mode in the equipment is questionable because of large errors encountered due to its inadvertant misuse and the small benefits, if any, gained from it. The one type of mistake that cannot be eliminated by equipment design is operator errors in the entry of present position. However, the system is relatively insensitive to initial position errors of 500 nmi in horizontal location and 100,000 feet in altitude.

In summary, the pilot can enter an incorrect position by 10° in latitude, 10° in longitude, 100,000 feet in altitude, and 15-minute incorrect time and still acquire the satellites; but if he enters the wrong day or flies while in calibration mode, the set will either not acquire the satellites or provide incorrect, erratic information.

SUMMARY OF RESULTS

The test results in relationship to the FRP technical issues are contained in the following paragraphs.

1. <u>POSITION ACCURACY</u>: A summary of the test results are presented in table 19 with respect to the FRP accuracy requirement, and table 20 with respect to Advisory Circular (AC) 90-45A error criteria. No wild point editing or filtering were employed in obtaining the results. The accuracy of the ground tracking radar was comparable to the accuracy of the GPS Z-set. The Z-set mean clock bias rate was 27 nanoseconds per second measured over a 2.3-hour period. The results of the tabular summaries from tables 19 and 20 are listed here.

Using four-satellite navigation with or without aided altitude and HDOP ≤ 10, the GPS Z-set receiver position accuracy was 87 meters (mean +2 standard deviations). This meets: (1) FRP current and projected future criteria for en route, terminal, and nonprecision approach (reference table 19); and (2) AC 90-45A error criteria for all phases of en route, terminal, and nonprecision approach (see table 20).

Using four-satellite navigation with or without aided altitude and HDOP's between 10 and 20, the Z-set receiver position accuracy was 143.5 meters (mean +2 standard deviations). This apparently meets the requirements of FRP and AC 90-45A for en route and terminal, but there are insufficient data to make a firm determination.

Using three-satellite navigation, continuous altitude input and effective HDOP's less than four (altitude input is considered as a fourth satellite at the center of the earth), the Z-set receiver position accuracy was 104 meters (mean +2 standard deviations). Wild point editing and filtering would reduce this considerably below 100. This meets: (1) FRP current and projected future requirements for en route, terminal, and nonprecision approach (reference table 19); and (2) AC 90-45C requirements for all phases of en route, terminal, and nonprecision approach (reference table 20). (Three-satellite configurations with higher effective HDOP's than four were not tested during the test period.)

Using three-satellite navigation, without continuous altimeter input, flown at constant altitude, and effective HDOP less than four (assumes a fourth satellite at the center of the earth providing a constant altitude input), the Z-set receiver position accuracy was 38 meters (mean +2 standard deviations). This meets: (1) FRP current and projected future requirements for en route (reference table 19); and (2) AC 90-45C requirements for all phases of en route (reference table 20).

Although a mean and 2 standard deviation of 38 meters appear to meet the requirements for terminal and nonprecision approach, it is not applicable to these flight environments because they involve relatively quick changes in altitude. When changing altitude, the position accuracy increases to 992 meters (mean +2 standard deviations), which indicate that three-satellite navigation without altitude input could still meet the en route requirements of the FRP and AC 90-45A (reference tables 19 and 20).

2. RADIOFREQUENCY INTERFERENCE: The Z-set exhibited catastrophic degradation from -95 dBm continuous wave interference within ±1 MHz of the C/A center frequency of 1575.42 MHz. A potential problem exists within 35 nmi of the 5 megawatt TV channel 23, which conforms to FCC 60 dB attenuation of harmonics and spurious emissions. During RFI tests and periods when the Z-set was receiving signals from four satellites and collected ephemeris is from three, the system provided erroneous information, but the EPE remained low and the system status lights indicated acceptable performance (reference segments 54 and 56).

3. MULTIPATH EFFECTS: No results of tests where significant errors occurred could be attributed to multipathing.

4. VEHICLE DYNAMICS EFFECTS: The GPS receiver was not catastrophically affected by acceleration and banks angles of 50°. Although affected during high acceleration periods with increase oscillations about the true position, the receiver did not lose track and settled down within a minute of the maneuver (reference figures 28,

29, and 30). For 15°, 30°, and 50° banks with HDOP ≤25, mean and standard deviations were 57.1 meters and 121.9 meters, respectively. During nonprecision approaches when both altitude change and banking were occuring (tear drop approach), no unique problems of accuracy resulted.

When operating with three healthy satellite signals and without continuous attitude input while changing attitude, the Z-set performed with significantly less accuracy (reference table 20). Generally, the altitude parameter appears to be two to three times more sensitive to acceleration than horizontal parameters (reference figures 17 and 30).

5. SIGNAL ACQUISITION AND TRACKING CONTINUITY: The ground acquisition time varied between 3 and 14 minutes, with an average time of 6.4 minutes (reference table 3). On numerous occasions the set required repeated attempts or the collection of a new almanac before acquisition was achieved. Improper almanac data given to the satellites by GPS ground control segment, since corrected, could have caused these acquisition problems. Almanac collection times varied between 3 and 24 minutes, with an average of 8.4 minutes (reference table 4).

The airborne acquisition time varied from 3 to 14 minutes and the collection of almanac in the air took 5 minutes (reference tables 3 and 4).

The system held ephemeris data for up to 1 minute if the antenna was disconnected and, under the condition of held ephemeris, reacquired in 1 to 3 minutes.

The Z-set is not always transparent to satellite constellation change (reference figure 5) and the effect, as observed, could be disturbing to a pilot on approach.

The Z-set enters, at times, a state of confusion where it receives signals from four satellites, collects ephemeris from only three satellites, and provides erroneous navigation information to the pilot. Figures 39 and 40 illustrate this problem.

RFI also effects the Z-set tracking capability as previously cited.

6. SIGNAL COVERAGE: Satisfactory performance was achieved with four satellite signals for HDOP less than 10 (reference table 8). Further study will be required to determine the amount of worldwide coverage that would be available for HDOP of 10 or less. Further, acceptable performance with three-satellite signals plus automatic altitude input could provide an additional safety factor for the coverage area.

7. PROPAGATION: Not tested.

8. NOISE EFFECTS: Data from spectrum analyzer monitoring of east coast airports showed ambient RFI levels at approximately -115 dBm at antenna terminals for a 300 kHz bandwidth, and random noise peaks at approximately -100 dBm. No observed Z-set performance degrading effects were observed coincidently with noise peaks or ambient RFI at -115 dBm.

9. INSTALLATION REQUIREMENTS: The Z-set was operated from two types of antennas located close to each other and at a location where aircraft banks would result in shielding of satellites. Both antennas performed satisfactorily at their respective locations during the nonprecision approaches (reference figure 37).

10. ENVIRONMENTAL EFFECTS: The Ball Brothers microstrip antenna was protected by a radome while mounted on the aircraft. The antenna performed satisfactorly when surfaced with up to 0.25 inch of ice during laboratory testing (reference figure 38).

11. HUMAN ENGINEERING FACTORS: The GPS Z-set receiver can change from one satellite constellation to another automatically without alerting the pilot before changeover. Since changeover is not always smooth and the position information could contain considerable variation, the changeover, at times, will be disturbing to the pilot, especially during nonprecision approaches. Figure 6 illustrates the variation in position during changeover.

The GPS system is relatively insensitive to initial position entry errors. If entry is made for the coordinates for Chicago, Illinois, Detroit, Michigan, or Jacksonville, Florida, while in Atlantic City, New Jersey, the system will acquire the satellites and correct the position in the same amount of time as it would have if the correct coordinates had been entered. Table 17 presents a summary of test results.

The GPS system is sensitive to the initial entry of time. If the time is entered incorrectly by 30 minutes or more, the acquiring of satellites is questionable and unpredictable.

The GPS receiver can be flown using information from satellites declared unhealthy if the operator fails to collect an almanac prior to flight. This will degrade the overall navigation performance of the GPS receiver to unacceptable limits. The set uses the almanac data to determine if a satellite is healthy and if it can be used for navigation.

The EPE determined by the Z-set is misleading at times and should not be the sole criterion for acceptable system performance. The equipment status lights indicating navigation, standby, and calibration modes are hard to detect and lead to operator errors by being overlooked.

CONCLUSIONS

1. A low cost properly designed Global Positioning System (GPS) receiver (corrects observed problems with Z-set) can easily meet the Federal Radionavigation Plan (FRP) requirements for en route, terminal, and nonprecision approach when operating with an undegraded signal and other four satellites with horizontal dilusion of precision (HDOP) less than 10 or three satellites with continuous altitude input and an effective HDOP less than four (highest value of HDOP tested with three satellites during test periods). The FRP technical issues are discussed under the "Summary of Results" in the body of this report. Tables 8 and 19 provide supporting data for this conclusion.

2. A low cost properly designed GPS receiver (corrects observed problems with Z-set) can easily meet the accuracy requirements of Federal Aviation Administration (FAA) Advisory Circular (AC) 90-45A for en route navigation and nonprecision approach when using an undegraded course acquisition (C/A) signal, and either a four-satellite constellation with an HDOP less than 10 or three satellites with

continuous altitude input and an effective HDOP less than 4. Flight technical error (FTE) when using a GPS receiver was not addressed during these tests, but will be addressed in the forthcoming General Aviation Test in November 1982. Table 8 and figure 13 provides supporting data for this conclusion.

3. The Z-set performed with significantly less accuracy when operating with an undegraded C/A signal and three healthy satellites without continuous altitude input when the aircraft changed altitudes and the pilot did not manually enter new altitude information.

4. There is a potential problem with radiofrequency interference (RFI) if other systems emit RF signals above -95 decibels above 1 milliwatt (dBm) in ±1 megahertz (MHz) of GPS C/A center frequency (1575.42 MHz) in a region that aircraft will use GPS systems for navigation.

5. The GPS receiver was not catastrophically affected by acceleration and bank angles of 50°. Although affected during high acceleration periods with increase oscillations about the true position, the receiver did not lose track and settled down within a minute of the maneuver.

RECOMMENDATIONS

1. Maintain strict control over radiofrequency (RF) emissions in the Global Positioning System (GPS) frequency band.

2. Determine the extent of worldwide coverage for different values of horizontal dilusion of precision (HDOP), 10, 15, 20, and above, and number of satellites required to obtain certain HDOP levels. Examine GPS receiver navigation degradation as different numbers of satellites fail for different geographic locations and phases of navigation.

3. Consider the following GPS receiver design features for all GPS civil aviation receivers:

a. Automatic and periodic collection of the almanac and monitoring satellite health status.

b. Smooth transition when changing satellite configuration.

c. Delete, modify, or reaccess calibration mode in airborne receivers.

d. Automatic initialization of the GPS receiver at turn-on by incorporation and utilization of a battery operated calendar clock and last remembered position when system was turned off.

e. Unambiguous and clear annunciation of system status lights.

f. Incorporate an improved waypoint entry system into GPS airborne equipment such as the existing 3- to 5-alphanumerical character system used for airport and waypoint identification. This improved waypoint entry system should be devised to facilitate operation in the present very high frequency omnidirectional radio range (VOR)/distance measuring equipment (DME) environment by allowing pilots to enter VOR radial intersection into the system or to fly vectors from certain points.

TABLE 1. Z-SET PARAMETERS

Operational Parameters	Characteristics
RF signal input level (to antenna)	-130 to -120 dBm
Frequency (L_1)	1575.42 ±10 MHz
Polarization	Right hand circularly polarized
Antenna gain	0 dBic minimum from 30° to 90° (above the horizon) -1.5 dBic minimum from 5° to 30°
Antenna coverage	Hemispherical
Antenna axial ratio	<3 dB at 90° <5 dB at 45° <16 dB at 5°
Pseudorange measurement accuracy	$\leq$50 meters (2σ)
Vehicle velocity dynamics	$\leq$400 m/s
Vehicle acceleration dynamics	$\leq$5 m/s^2
Initial signal acquisition time	$\leq$300 seconds
Jamming to signal power ratio	25 dB
Preamplifier bandwidth selectivity at L_1	24 ±8 MHz at 3 dB point $\leq$50 MHz at 70 dB point
Preamplifier gain at L_1	30 to 39 dB

Displayed Parameters	Characteristics
Test	Check LED operation
Estimated position error	Calculated from the Kalman filter covariance matrix resolution to 0.01 nmi
Distance to waypoint	Resolution to 0.1 nmi
Bearing to waypoint	Resolution to 0.1°
Latitude	Resolution to 1 arc second
Longitude	Resolution to 1 arc second
Altitude	Resolution to 1 foot
Waypoint magnetic variation	Resolution to 0.1°
Ground speed	Resolution to 1 knot
True ground track	Resolution to 0.1°
Day/time	GPS time to 1 second
Unmarked 6 o'clock position	Fault messages and satellite data

Note: dBm = decibels referenced 1 milliwatt
dBic = decibels referenced to isotropic antenna
m/s = meters per second
LED = light-emitting diode
nmi = nautical miles

TABLE 2. MAJOR Z-SET RELATED PARAMETERS RECORDED

PZ	Z-set derived position utilizing earth-centered earth-fixed coordinates (ECEF) converted to latitude, longitude, and altitude in WGS-72 coordinate systems.
SN	Number of each satellite in the constellation selected by the Z-set providing data.
NSD	Number of satellites presently providing data.
NSE	Number of satellites for which ephemeris data has been collected.
DX, DY, DZ	Difference between Z-set derived position and the known surveyed position of the antenna in three orthogonal directions. DX is the northerly difference, DY is the easterly difference, and DZ is the altitude difference.
2D	Horizontal difference between the Z-set derived position and the known surveyed position of the antenna.
3D	Spacial difference between the Z-set derived position and the known surveyed position of the antenna.
GS	Z-set derived ground speed.
GTK	Z-set derived ground track.
Z (Dwell)	Z-set dwell counters for each satellite (increased for good data quality, decreased for poor data quality).
Z (Count)	Z-set up-down (increased with poor data quality, decreased with good data quality).
HDOP	Horizontal dilution of precision value for satellite configuration selected.
GDOP	Geometric dilution of precision value for satellite configuration selected.
EPE	Estimated position error of the Z-set.
GPS (Time)	GPS time in tenths of seconds from the Z-set.

TABLE 3. ACQUISITION TIMES

Date 1981	Elapse Time (min)	Date 1981	Elapse Time (min)	Date 1981	Elapse Time (min)
3/9	13	3/10	11	3/11	7
3/17	6, 6, 5, 6	3/19	9	3/23	10
3/24	8	3/25	11	3/26	13, 8
3/27	8	4/7	5	4/8	5, 8
4/10	11	4/22	4	4/24	4
5/2	3, 6	5/3	4, 4	5/9	5, 12
5/10	4, 13	5/11	5	5/12	4, 8
5/14	4, 2	5/20	10, 5	5/21	8
5/28	5	5/29	7, 4	6/22	12, 4, 4
6/22	8, 2, 9 (air)	6/23	4	6/24	14 (air)
6/26	4, 9	6/30	6, 19	7/1	8, 13
7/2	7	7/6	6	7/9	2
7/15	3, 3	7/17	4(17x), 3, 3, 3, 3*	7/17	6, 8, 2, 2, 2, 2, 2
8/11	4	8/18	4	8/19	3
8/20	5	8/26	3	10/14	7, 7, 6, 3
10/26	5, 6, 6	10/27	11, 6, 5, 7, 7	10/29	7, 5, 7
10/30	9, 7, 7, 7, 8, 6, 6	11/9	10, 6, 7, 8, 7, 7	11/17	14, 3, 4, 7
11/18	10, 2, 7, 7, 7, 7				

Note: Average time is 6.4 minutes and depends in part on Z-set's RF oscillator temperature.

*Four-minute acquisition occurred 17 times that day.

TABLE 4. ALMANAC COLLECTION TIMES

Date 1981	Elapse Time (min)	Date 1981	Elapse Time (min)
3/23	6	4/30	6
5/3	9	5/9	9
5/10	6	5/12	16
5/22	5	5/29	19
6/22	3	6/22	20 (after SS)*
6/23	4	6/25	8
6/26	24	6/29	5, 6
6/30	3	7/13	5
7/15	5 (in air)	7/16	13
7/17	10	8/18	6
8/19	9	8/20	4
8/26	4	10/14	20
10/26	5	10/27	9
11/29	4	11/10	5
11/17	6	11/18	5

Note: Average time is 8.4 minutes.

*SS = search the sky mode. The Z-set in this mode searches the sky systematically until a satellite signal is found. It collects an almanac from this satellite and acquires the rest of the satellites in normal fashion. Search the sky mode will occur when the receiver does not have an almanac stored or when the operator directs it.

TABLE 5. LABORATORY MONITORING DATA SUMMARY

Test Conditions				Results		
			HDOP/Time	Horizontal (meters)		
Date	Status	Digital Altimeter	Interval (a.m.)	(2D) Mean	Std. Dev.	No. of Data Points
4/25/81	4:4	No	1.8 to 1370 3:08 to 5:57	12.1	3.1	7,254
5/3/81	4:4	No	1.8 to 1081 2:45 to 5:20	10.6	16.0	6,664
5/5/81	4:4	No	1.8 to 1088 2:34 to 5:13	7.2	26.8	6,816
5/7/81	4:4	No	1.8 to 1425 2:49 to 5:10	20.0	62.6	5,659
5/11/81	4:4	No	1.8 to 1195 2:21 to 4:49	15.8	23.9	6,362
2/12/82	3:3	No	7:51 to 9:07	13.2	49.0	3,761
2/23/82	3:3	Yes	7:25 to 8:23	18.9	10.0	2,867

Note: All data taken in navigation mode except for April 25 data, which was taken in calibration mode. The accuracy of the mean varies slightly from night to night under the same apparent conditions (May 3, 5, 7, and 11, 1981) and is attributed to the accuracy of the ephemeris data, satellite signal strength at the antenna location and the repeatability of the Z-set. The standard deviation varies more with the conditions of the test. The standard deviation is significantly lower when in calibration mode (April 25 data) than navigation mode (May 3, 5, 7, and 11 data). When operating with three satellites the standard deviation is significantly lower with altitude input (February 23 data) than without altitude input (February 12 data).

All data were taken for the entire four-satellite window when four satellites were available (first five readings). When only three satellites were monitored (last two readings), data were taken for the entire period that the three satellites were available.

TABLE 6. DETAILED LABORATORY MONITORING STATISTICS FOR APRIL 25, 1981

Time Interval: 3:8:0 to 5:57:0 No. of Data Points: 7254

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	0.5	2.1	-6.8	6.8
DY	-12.0	2.3	-25.4	8.5
DZ	2.1	3.9	-5.2	18.5
2D	12.1	3.1	8.5	25.8
3D	12.2	5.0	8.7	31.5
EPE	5.3	1.0	5.2	18.1
GVAR	6.5	1.4	6.2	23.8
Speed	0	0.0	0	0
Altitude	39.5	12.8	-14.4	63.3
HDOP			1.8	1370.0
GDOP			4.8	3186.0

NOTE: DX, DY, DZ, 2D, 3D, EPE, and GVAR are given in meters; speed is given in knots (nmi per hour); altitude is given in feet; other parameters are dimensionless. System was in calibration mode.

TABLE 7. DETAILED LABORATORY MONITORING STATISTICS FOR MAY 5, 1981

Time Interval: 2:34:0 to 5:13:0 No. of Data Points: 6816

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	-3.1	17.7	-87.3	26.3
DY	-6.5	20.2	-39.0	81.4
DZ	23.3	43.7	-70.4	200.3
2D	7.2	26.8	0.0	116.0
3D	24.3	51.3	2.9	228.5
EPE	47.0	45.6	18.0	264.1
GVAR	51.7	48.4	19.6	281.8
Speed	0.2	0.1	0	1.4
Altitude	-30.1	143.3	-610.9	277.2
HDOP	37.6	128.9	1.8	1088.0
GDOP	44.1	143.2	4.8	2515.0

NOTE: DX, DY, DZ, 2D, 3D, EPE, and GVAR are given in meters; speed is given in knots (nmi per hour); altitude is given in feet; other parameters are dimensionless.

TABLE 8. FLIGHT DATA SUMMARY

Test Conditions				Results		
				Horizontal (meters)		
Date 1981	Flight Profile	System Status	HDOP/Time Interval	(2D) Mean	Std. Dev.	No. of Data Points
7/13	Rectangle	4:4	1.8 to 10 2152 to 0004	10.5	25.5	6,234
7/13	Rectangle	4:4	10 to 17 0004 to 0013	31.2	60.5	427
7/6	Rectangle	4:4	2.0 to 10 2317 to 0032	11.4	22.6	3,444
7/6	Rectangle	4:4	10 to 20 0032 to 0044	8.3	86.1	528
7/8	Rectangle/ Orbit/ Approaches	4:4	1.8 to 10 2302 to 0024	13.4	44.4	3,953
			10 to 18 0024 to 0034	10.3	44.7	461
7/9	Rectangle/ Orbit	4:4	1.8 to 3.2 2201 to 2321	21.8	55.9	3,644
6/26	Nonprecision Approaches	4:4	1.8 to 2.9 2320 to 0049	3.7	17.4	4,187
6/24	Rectangle	4:4	1.8 to 2.6 2330 to 0043	5.5	18.1	1,116
7/15	Bank Terms	4:4	15.3 to 44 2345 to 0015	51.1	121.9	1,289
7/3	Rectangle/ Orbit/ Approaches	3:3*	1.8 to 3.0 2251 to 042	12.2	45.9	5,163
7/14	Constant Altitude	3:3**	2242 to 2304	7.4	15.4	1,097
7/14	Changing Altitude	3:3**	2215 to 2240	52.6	233.0	1,247

Note: Wild point editing was not employed nor was radar data smoothed. The accuracy of the mean is normally better for HDOP below 10 than above 10. But for any short period of time, this relationship may not hold. The standard deviation is much higher for HDOP above 10 than below 10, as can be seen from data on July 6, 8, and 13. It is extremely important to look at the delta mean plots of the above periods to fully evaluate the effects of different conditions on system performance. For instance, July 9 has one sharp peak at 22:12 in position difference between radar and GPS readings, which caused an abnormally high standard deviation reading for the period. For July 3 data HDOP was computed assuming a fourth satellite at the center of the earth to represent the continuous altitude input.

*With altitude input
**With no altitude input

TABLE 9. DETAILED FLIGHT STATISTICS FOR JULY 13, 1981

Time Interval: 21:52:10 to 0:4:40   No. of Data Points: 6234

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	-9.8	17.8	-390.8	87.3
DY	-3.7	18.3	-303.5	213.1
DZ	39.0	48.5	-554.7	486.1
2D	10.5	25.5	0	427.8
3D	40.4	54.9	2.1	592.2
EPE	69.1	75.0	19.9	570.2
GVAR	77.7	81.9	22.2	617.3
Speed	223.8	21.6	141.4	295.5
Altitude	9133.8	1682.4	3816.6	12700.8
HDOP			1.8	10.0
GDOP			4.5	30.4

Time Interval: 0:4:40 to 0:13:25   No. of Data Points: 427

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	-23.7	40.3	-322.1	97.5
DY	20.3	45.1	-182.9	389.5
DZ	83.4	148.4	-431.5	1330.2
2D	31.2	60.5	0	505.5
3D	89.1	160.3	4.5	1423.0
EPE	329.0	205.4	145.3	1054.8
GVAR	354.5	221.0	156.4	1139.4
Speed	218.8	16.8	101.8	309.8
Altitude	7712.6	478.1	3706.8	9239.8
HDOP			10.0	17.0
GDOP			30.2	47.8

Note: DX, DY, DZ, 2D, 3D, EPE, and GVAR are given in meters; speed is given in knots (nmi per hour); altitude is given in feet; other parameters are dimensionless.

TABLE 10. DETAILED FLIGHT STATISTICS FOR JULY 6, 1981

Time Interval: 23:17:5 to 0:32:30 No. of Data Points: 3444

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	-11.1	16.0	-151.7	76.3
DY	-1.8	16.0	-109.1	149.2
DZ	39.5	55.4	-349.7	377.4
2D	11.4	22.6	0	212.8
3D	41.1	59.8	1.8	381.3
EPE	90.3	69.1	22.8	446.5
GVAR	100.7	75.5	25.6	483.5
Speed	228.8	20.1	163.0	295.5
Altitude	7186.8	1483.5	629.6	283.6
HDOP			2.0	10.0
GDOP			5.4	30.6

Time Interval: 0:32:35 to 0:44:0 No. of Data Points: 528

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	-8.0	53.0	-197.5	395.1
DY	-2.1	67.9	-648.8	181.8
DZ	21.3	151.5	-708.8	597.2
2D	8.3	86.1	2.9	759.6
3D	22.9	174.3	5.8	774.7
EPE	331.0	185.6	147.5	968.8
GVAR	356.6	199.5	159.1	1040.2
Speed	163.4	10.3	142.5	200.0
Altitude	1614.3	705.9	-165.4	4099.5
HDOP			10.0	20.0
GDOP			30.7	57.9

Note: DX, DY, DZ, 2D, 3D, EPE, and GVAR are given in meters; speed is given in knots (nmi per hour); altitude is given in feet; other parameters are dimensionless.

TABLE 11. DETAILED FLIGHT STATISTICS FOR JULY 8, 1981

Time Interval: 23:2:38 to 0:24:31   No. of Data Points: 3953

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	-12.8	39.3	-512.0	269.6
DY	3.8	20.6	-287.9	154.7
DZ	1.1	58.7	-605.0	366.1
2D	13.4	44.4	0	526.9
3D	13.4	73.6	2.1	659.2
EPE	86.6	90.5	21.3	672.9
GVAR	96.0	98.6	23.9	731.4
Speed	205.7	33.0	115.6	264.1
Altitude	5820.4	2805.3	314.2	8599.1
HDOP			1.8	10.0
GDOP			5.1	30.5

Time Interval: 0:24:42 to 0:34:0   No. of Data Points: 461

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	4.2	29.1	-152.6	117.8
DY	-9.4	33.9	-133.4	168.7
DZ	56.0	96.3	-467.6	524.7
2D	10.3	44.7	0.8	227.5
3D	57.0	106.2	6.8	571.9
EPE	251.1	154.6	131.9	894.5
GVAR	270.7	166.9	142.3	964.4
Speed	169.2	13.8	143.9	258.1
Altitude	2283.6	1276.2	-146.6	5548.3
HDOP			10.0	18.0
GDOP			30.6	50.3

Note: DX, DY, DZ, 2D, 3D, EPE, and GVAR are given in meters; speed is given in knots (nmi per hour); altitude is given in feet; other parameters are dimensionless.

TABLE 12. DETAILED FLIGHT STATISTICS FOR JULY 9, 1981

Time Interval: 22:1:40 to 23:21:49 No. of Data Points: 3644

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	-21.5	40.1	-655.3	891.0
DY	4.0	38.9	-1410.9	490.2
DZ	33.6	34.4	-124.8	285.8
2D	21.8	55.9	0	1668.7
3D	40.1	65.6	7.5	1668.9
EPE	35.7	20.8	19.9	118.0
GVAR	41.5	25.2	22.2	139.6
Speed	249.4	12.6	209.0	286.8
Altitude	8831.6	1282.4	7404.8	10868.4
HDOP			1.8	3.2
GDOP			4.5	6.6

Note: DX, DY, DZ, 2D, 3D, EPE, and GVAR are given in meters; speed is given in knots (nmi per hour); altitude is given in feet; other parameters are dimensionless.

TABLE 13. DETAILED FLIGHT STATISTICS FOR JUNE 26, 1981

Time Interval: 23:20:0 to 0:49:0 No. of Data Points: 4187

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	-3.6	13.6	-172.1	242.5
DY	-0.8	10.8	-145.3	94.1
DZ	-4.4	25.6	-271.8	174.2
2D	3.7	17.4	0	275.5
3D	5.8	31.0	0.8	288.4
EPE	49.7	34.0	20.2	286.8
GVAR	57.0	38.2	22.6	322.3
Speed	147.6	10.4	102.4	189.6
Altitude	1540.6	285.0	510.5	2470.9
HDOP			1.8	2.9
GDOP			4.6	13.7

Note: DX, DY, DZ, 2D, 3D, EPE, and GVAR are given in meters; speed is given in knots (nmi per hour); altitude is given in feet; other parameters are dimensionless.

TABLE 14. DETAILED FLIGHT STATISTICS FOR JUNE 24, 1981

Time Interval: 23:30:5 to 0:43:0 No. of Data Points: 999

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	-5.0	12.1	-85.6	71.2
DY	-2.1	13.5	-69.8	115.7
DZ	39.6	38.6	-121.9	619.9
2D	5.5	18.1	0	144.0
3D	40.0	42.6	1.9	630.9
EPE	48.5	34.4	20.5	278.4
GVAR	56.1	39.9	22.9	316.4
Speed	242.9	25.4	171.2	295.2
Altitude	9270.1	1122.1	7452.0	10728.2
HDOP			2.7	6.5
GDOP			1.8	2.6

Note: DX, DY, DZ, 2D, 3D, EPE, and GVAR are given in meters; speed is given in knots (nmi per hour); altitude is given in feet; other parameters are dimensionless.

TABLE 15. DETAILED FLIGHT STATISTICS FOR JULY 3, 1981

Time Interval: 22:51:40 No. of Data Points: 0:42:40

Parameters	Mean	Standard Deviation	Minimum	Maximum
DX	11.3	38.5	-406.1	290.8
DY	4.6	28.8	-277.4	283.9
DZ	762.4	44541.8	50.9	3200652.0
2D	12.2	45.9	0	495.5
3D	762.5	44541.9	77.8	3200652.0
EPE	34.0	7.0	29.8	118.5
GVAR	36.7	6.8	32.4	119.3
Speed	203.1	38.9	124.0	265.7
Altitude	3598.5	2006.8	-269.6	6629.4
HDOP*			1.8	3.0
GDOP				

Note: DX, DY, DZ, 2D, 3D, EPE, and GVAR are given in meters; speed is given in knots (nmi per hour); altitude is given in feet; other parameters are dimensionless.

*HDOP was computed assuming a fourth satellite at the center of the earth to represent the continuous altitude input.

TABLE 16. RFI EFFECTS ON Z-SET

Type of Signal	Frequency (MHz)	Signal Level at Antenna	Effect on Z-Set
Continuous Wave	1575.42 ± 1	-95 dBm	Position and ground speed erroneous
Continuous Wave	1570.42 1580.42	-60 dBm	Position and ground speed erroneous
Ambient RF Levels	1575.42 ± 30	-115 dBm (300 kHz-BW)	None
Ambient Random Noise Peaks	1575.42 + 30	-100 dBm (300 kHz-BW)	None

TABLE 17. BLUNDER ANALYSIS ENTRY ERRORS

Entry Mistakes Category	Type of Error	Magnitude of Error	Effect on Acquisition/Comment
Position Error	Latitude	+1°	None
	Latitude	+5°	None
	Latitude	+10°	None
	Longitude	+1°	None
	Longitude	+5°	None
	Longitude	+10°	None (1 out of 20 times failed to acquire, most likely the failure was caused by something else)
	Latitude	South for north	Catastrophic at our location
	Longitude	East for west	Catastrophic at our location
	Altitude	1,000 ft	None
		5,000 ft	None
		10,000 ft	None
		100,000 ft	None
Combined Position Error	Latitude	+10°	
	Longitude	+10°	None
	Altitude	100,000 ft	
Time Error	Wrong day	1 or more days	Catastrophic
	EST for GMT	5 hours	Catastrophic
	Wrong time	3 or more hours	Catastrophic
	Wrong time	2 hours	Normally catastrophic'
	Wrong time	1 hour	Marginal
	Wrong time	30 minutes	Marginal/usually corrects time
	Wrong time	15 minutes	None
Calibration Mode	Not selected during initiation on ground		No effect on acquisition, time to NAV mode-light is the same, standard diviation of position determination is at least five times greater (table 5)
	Selected while flying		Catastrophic latitude/longitude altitude display data jumps erratically for system already acquired
Navigation Mode	Flying in standby status (4:4 status)		Initial position errors decreased until system determines true position and system goes into navigation status, usually in less than 10 minutes
	Flying in standby status (4:3 status)		Large position errors continuously up to 80 miles or more

TABLE 18. LATITUDE/LONGITUDE ENTRY ERROR

Test Sequence No.	Latitude Error	Latitude Input	Longitude Error	Longitude Input	Elapse Time (min)	Final Status
1	0	39°26'58"N	0	74°34'00W	4	4:4
2	0	39°26'58"N	+10°	84°34'00W	4	Init
3	+10°	49°26'58"N	0	74°34'00W	5	4:4
4	0	39°26'58"N	+10'	74°44'00W	4	4:4
5	+10'	39°36'58"N	0	74°34'00W	6	4:4
6	0	39°26'58"N	-10'	74°24'00W	5	4:4
7	-10'	39°16'58"N	0	74°34'00W	4	4:4
8	0	39°26'58"N	+10"	74°34'10W	4	4:4
9	+10"	39°27'08"N	0	74°34'00W	4	4:4
10	80°	39°26'58"S	0	74°34'00W	5 (sec)	Init
11	0	39°26'58"N	150°	74°34'00E	7 (sec)	Init
12	+1°	40°26'58"N	0	74°34'00W	4	4:4
13	0	39°26'58"N	+1°	75°34'00W	4	4:4
14	-1°	38°26'58"N	0	74°34'00W	4	4:4
15	0	39°26'58"N	-1°	73°34'00W	8	4:4
16	+1'	39°27'58"N	0	74°34'00W	3	4:4
17	0	39°26'58"N	+1'	74°35'00W	3	4:4
18	-1'	39°25'58"N	0	74°34'00W	5	4:4
19	0	39°26'58"N	-1'	74°33'00W	4	4:4
20	0	39°26'58"N	0	74°34'00W	3	4:4
21	+10°	49°26'58"N	0	74°34'00W	4	4:4
22	0	39°26'58"N	+10°	84°34'00W	4	4:4
23	-10°	29°26'58"N	0	74°34'00W	15	STBY
24	0	39°26'58"N	-10°	64°34'00W	3	4:4
25	+1°	40°26'58"N	0	74°34'00W	4	4:4
26	0	39°26'58"N	+1°	75°34'00W	4	4:4
27	+1'	39°28'00"N	+1'	74°35'00W	4	4:4
28	-1'	39°26'00"N	-1'	74°33'00W	4	4:4
29	0	39°26'58"N	0	74°34'00W	4	4:4
30	+1'	39°28'00"N	+1'	74°35'00W	3	4:4

Note: The underline portion of the location is the incorrect portion of the location entered into the CDU.

TABLE 19. GPS COMPLIANCE CHART WITH FEDERAL RADIONAVIGATION PLAN CURRENT AND PROJECTED FUTURE REQUIREMENTS

			GPS Conditions		
Number of Satellites	4	4	3	3	3
HDOP Values	<10	10<HDOP<20	<4	<4	<4
Automatic Altitude Input	Yes	Yes	Yes	No	No
Aircraft Altitude Change	Yes	Yes	Yes	No	Yes
			GPS Measured Performance		
Number of Data Points	18,391	1,416	5,163	1,097	1,247
Mean (meters)	13	9	12	8	526
Standard Deviation (meters)**	37	67	46	15	233
Mean +2 Sigma (meters)	87	143	104	38***	992
FRP Requirements (meters) En Route (Subphase/2 drms Accuracy)			Compliance Determination		
Oceanic/4000+	Yes	Yes	Yes	Yes	Yes
Domestic/1000	Yes	Yes	Yes	Yes	Yes
Remote 1000	Yes	Yes	Yes	Yes	Yes
Terminal 1000	Yes	*	Yes	No	No
Approach-Nonprecision 100	Yes	No	Yes	No	No

Note: GPS system accuracy measured in test. System use accuracy not measured. FTE not included. Requirements taken from tables II-2.1 and 2.2 of Vol. II of FRP, March 1982.

*Not enough data to make a determination.

**Standard deviation could be smaller with additional filtering.

***Terminal and approach phases involve change in altitude to which the Z-set is sensitive when operating with three satellites. This data, taken without a change in altitude, was not used to determine compliance for terminal and approach phases.

TABLE 20. GPS COMPLIANCE CHART WITH FAA AC 90-45A

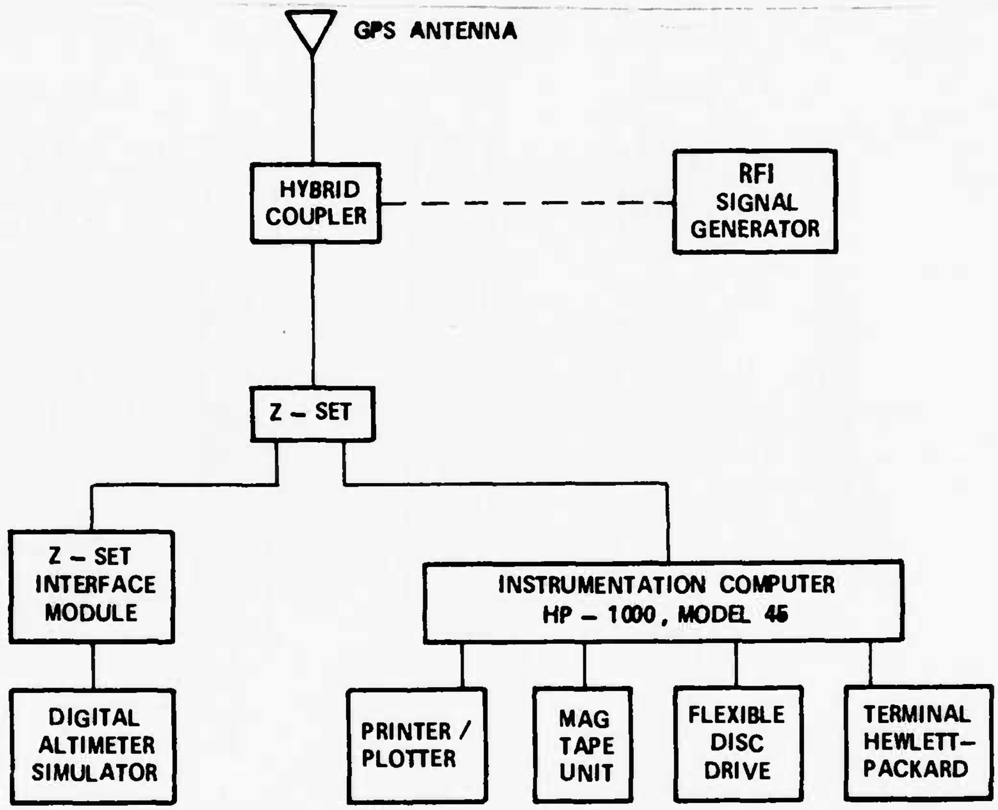
		GPS Conditions			
Number of Satellites	4	4	3	3	3
HDOP Values or FMOP	<10	10<HDOP<20	<4	<4	<4
Automatic Altitude Input			Yes	No	No
Aircraft Altitude Change	Yes	Yes	Yes	No	Yes
		GPS Measured Performance			
Number of Data Points	18,391	1,416	5,163	1,097	1,247
Mean (meters)	13	9	12	8	526
Standard Deviation (meters)*	27	67	46	15	233
Mean +2 Sigma (meters)	87	143	102	38***	992
AC 90-45A Requirements		Compliance Determination			
En Route					
Crosstrack (XTK) 2778	Yes	Yes	Yes	Yes	Yes
Along Track (ATK) 2778	Yes	Yes	Yes	Yes	Yes
Terminal					
Crosstrack 2037	Yes	Yes	Yes	Yes	Yes
Along Track 2037	Yes	Yes	Yes	Yes	Yes
Approach					
Crosstrack 555	Yes	**	Yes	No	No
Along Track 555	Yes	**	Yes	No	No

Note: Requirements derived from paragraphs 2a(3) and 2a(4) of appendix A of AC 90-45A. GPS accuracy measured. System use accuracy not measured. FTE not included.

*Standard deviation could be much smaller with additional filtering.

**Not enough data to make a firm determination.

***Terminal and approach phase involve changes in altitude to which the Z-set is sensitive when operating with three satellites. This data, taken without a change in altitude, was not used to determine compliance for terminal and approach phases.



NOTES: GPS ANTENNA WAS LOCATED AT A SURVEYED POINT.
ALTIMETER AND GENERATOR CONNECTED FOR SPECIFIC TEST ONLY.

82-64-1

FIGURE 1. LABORATORY TEST CONFIGURATION

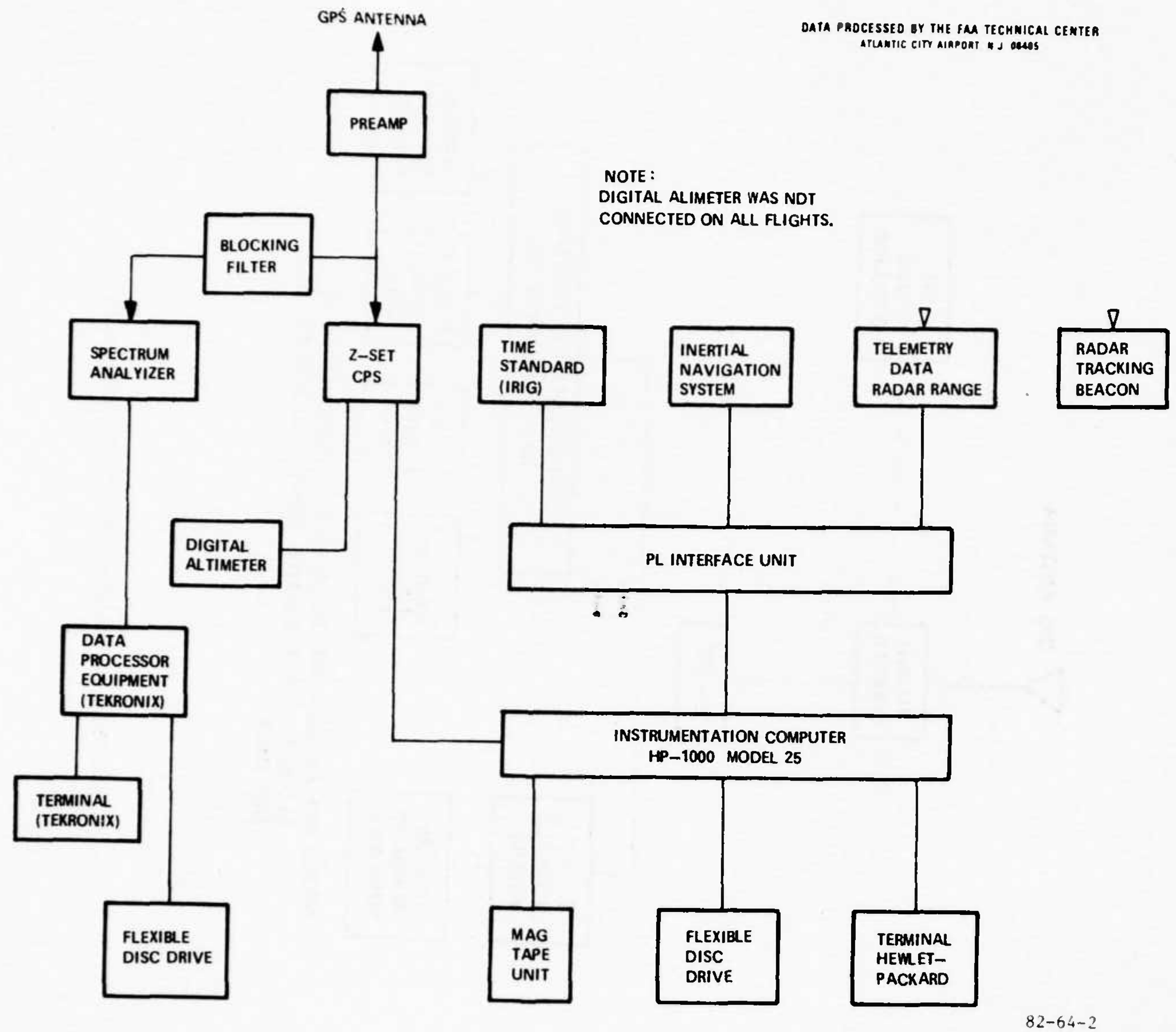


FIGURE 2. AIRBORNE TEST CONFIGURATION

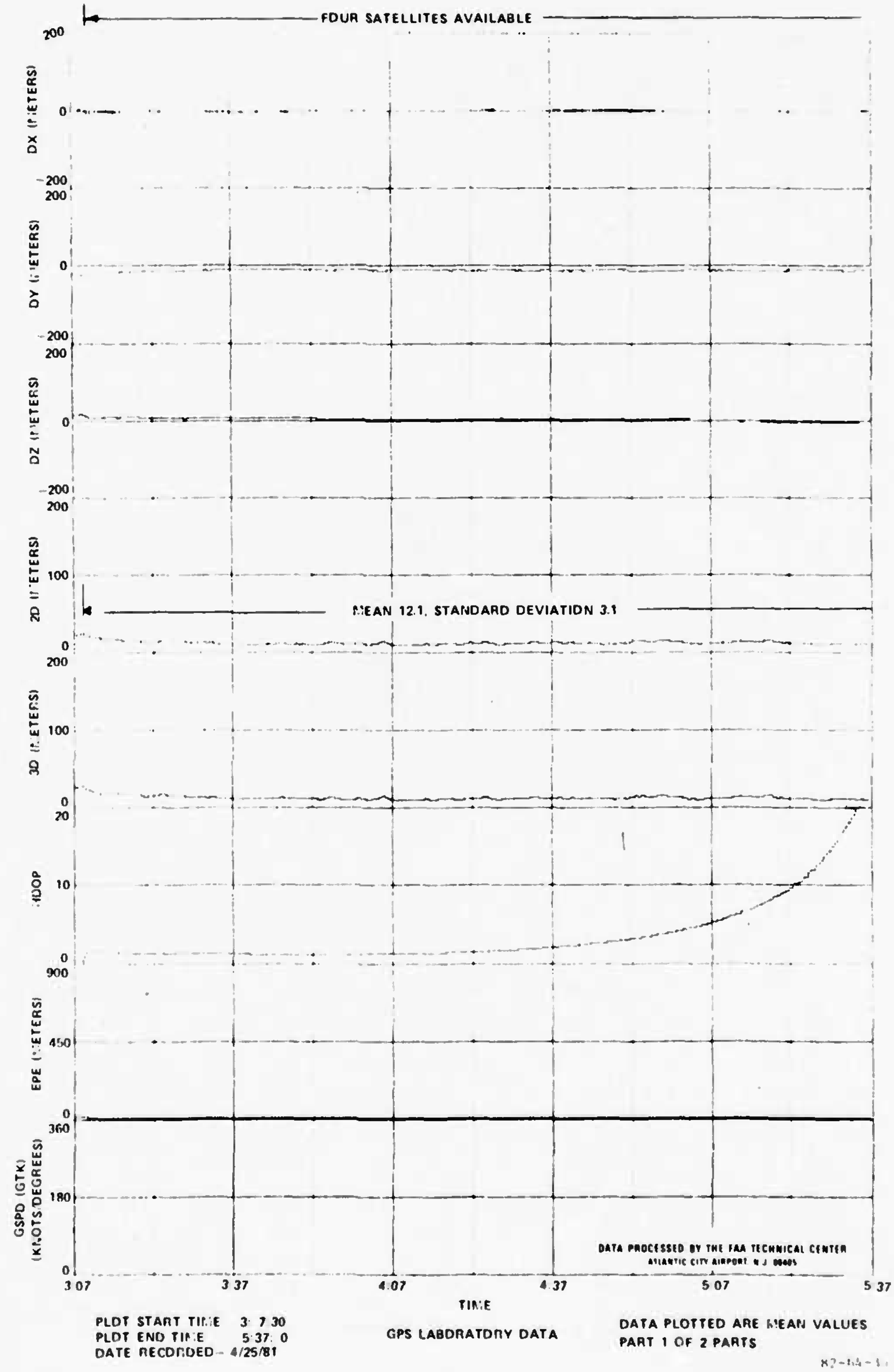


FIGURE 3. DELTA MEAN PLOT FOR CALIBRATION MODE ON APRIL 25, 1981 (SHEET 1 OF 2)

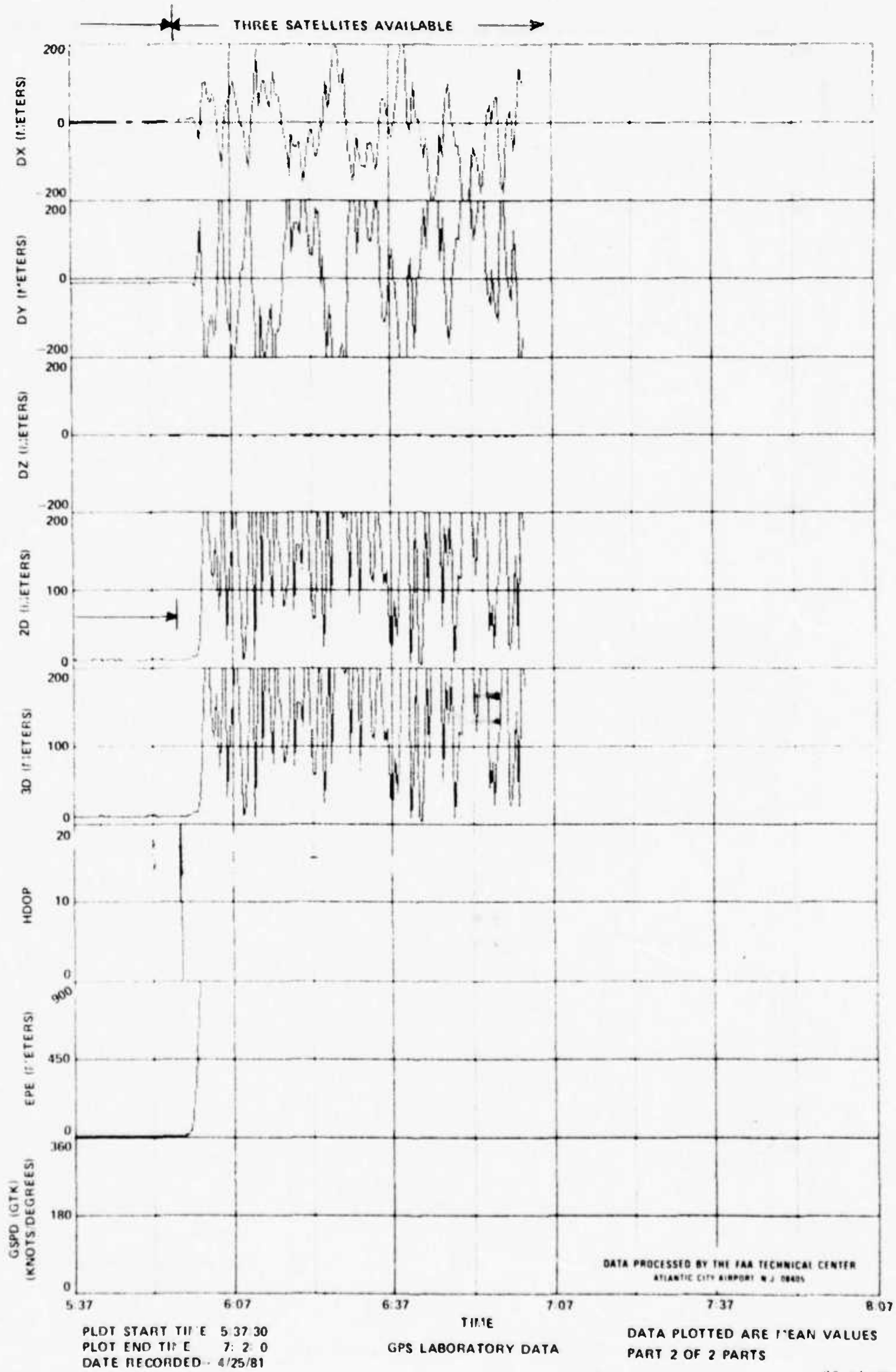


FIGURE 3. DELTA MEAN PLOT FOR CALIBRATION MODE ON APRIL 25, 1981 (SHEET 2 OF 2)

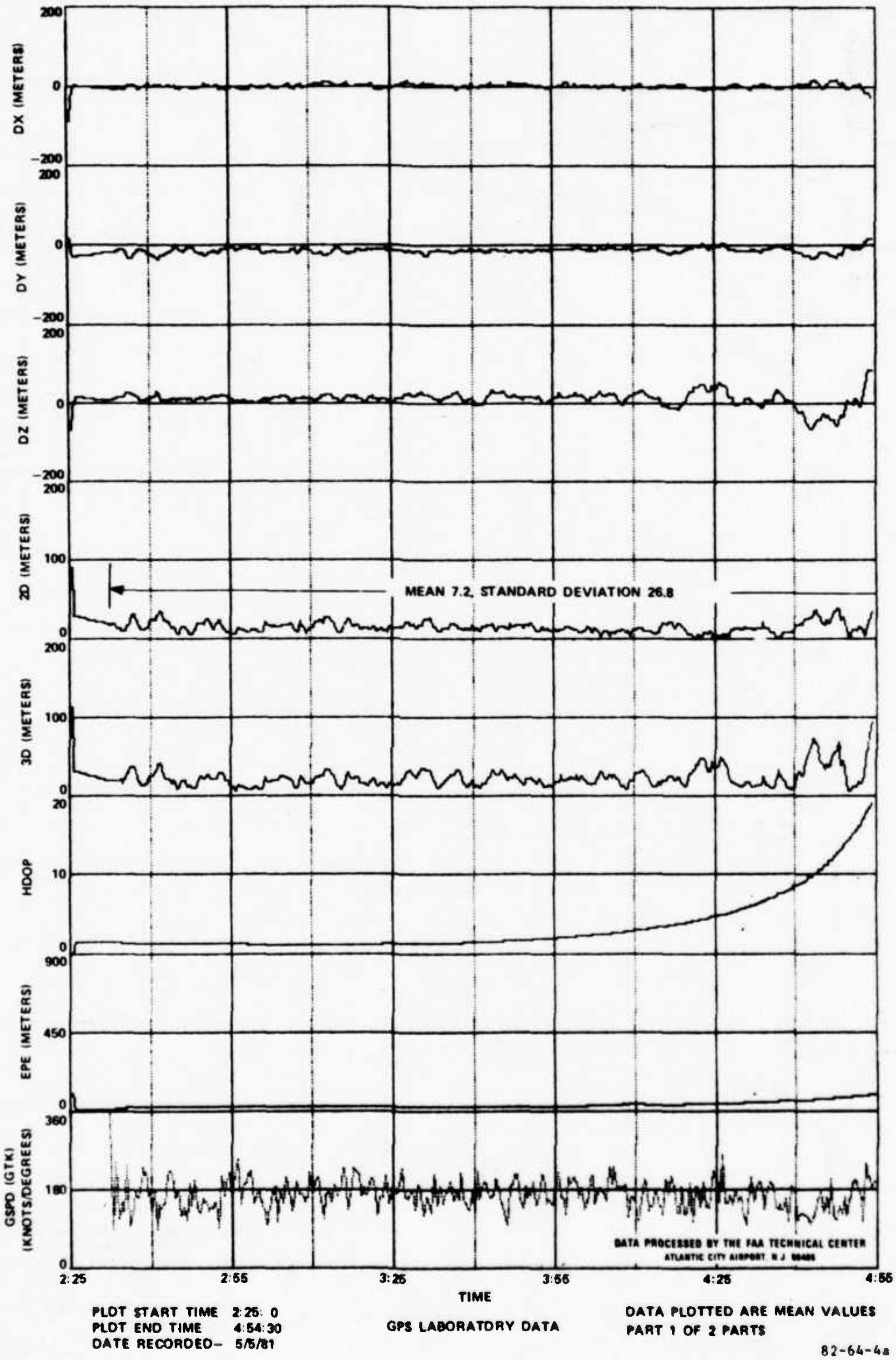


FIGURE 4. DELTA MEAN PLOT FOR NAVIGATION MODE ON MAY 5, 1981 (SHEET 1 OF 2)

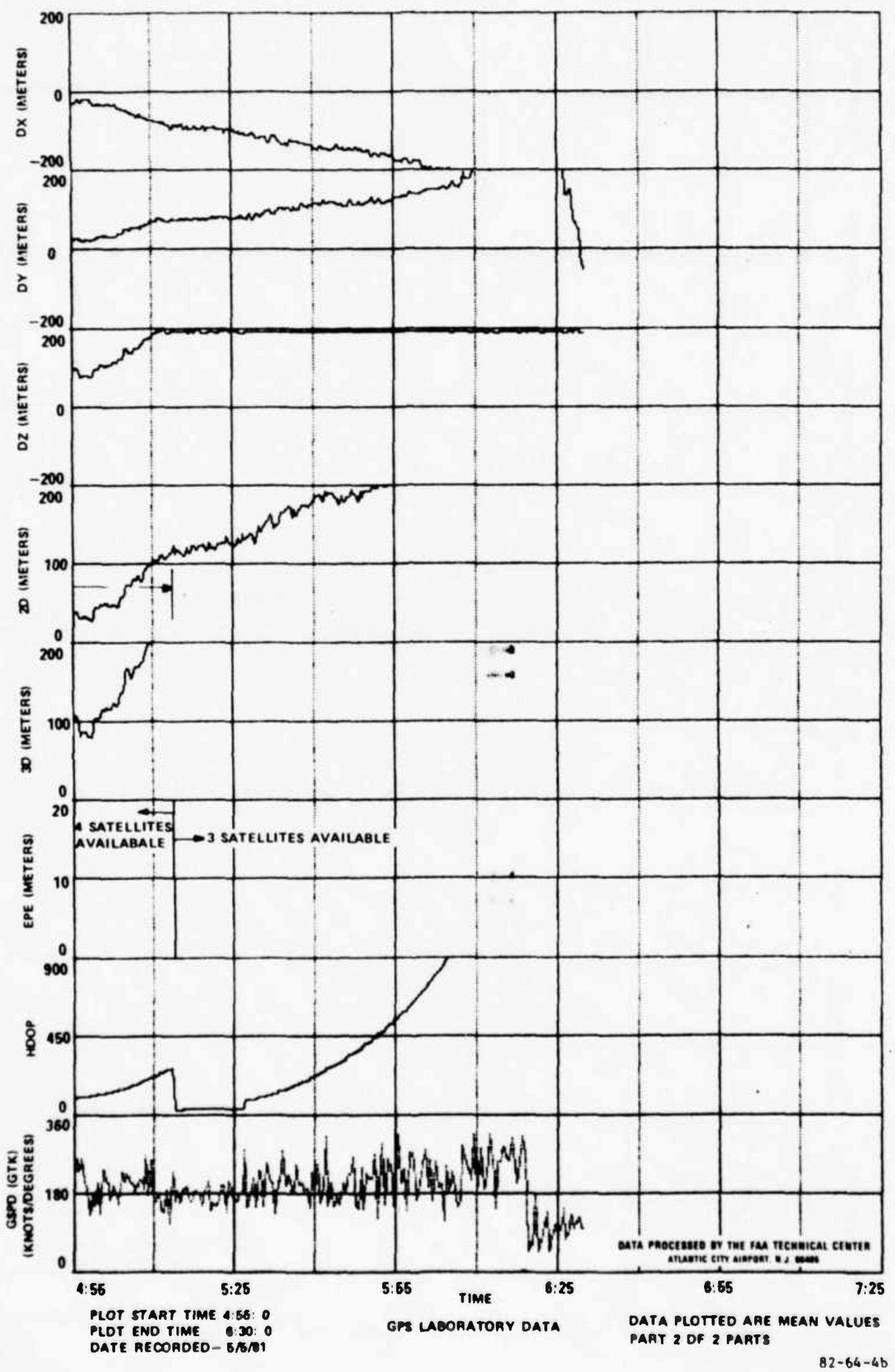


FIGURE 4. DELTA MEAN PLOT FOR NAVIGATION MODE ON MAY 5, 1981 (SHEET 2 OF 2)

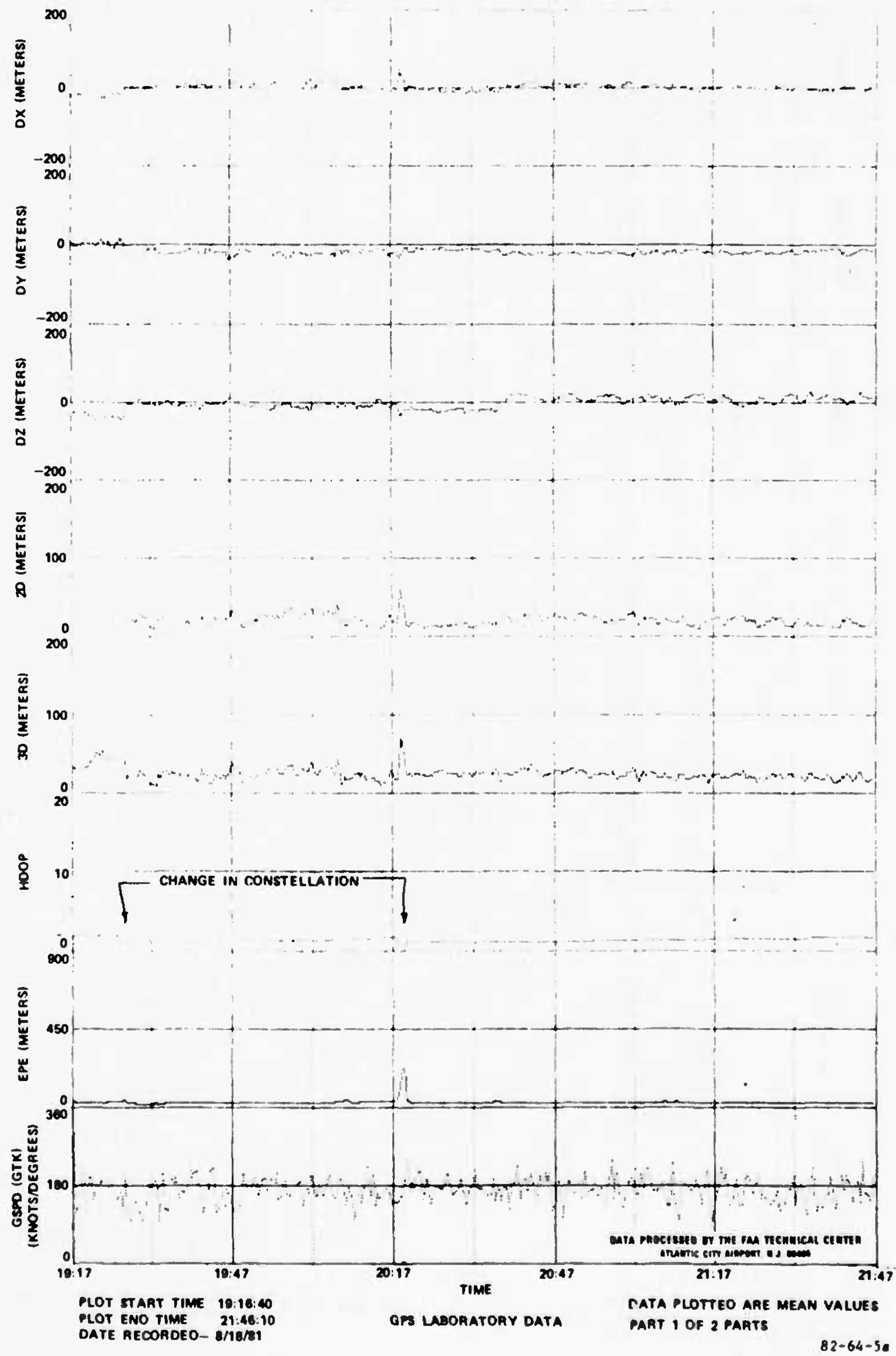


FIGURE 5. DELTA MEAN PLOT SHOWING CHANGE IN SATELLITE CONSTELLATION (SHEET 1 OF 2)

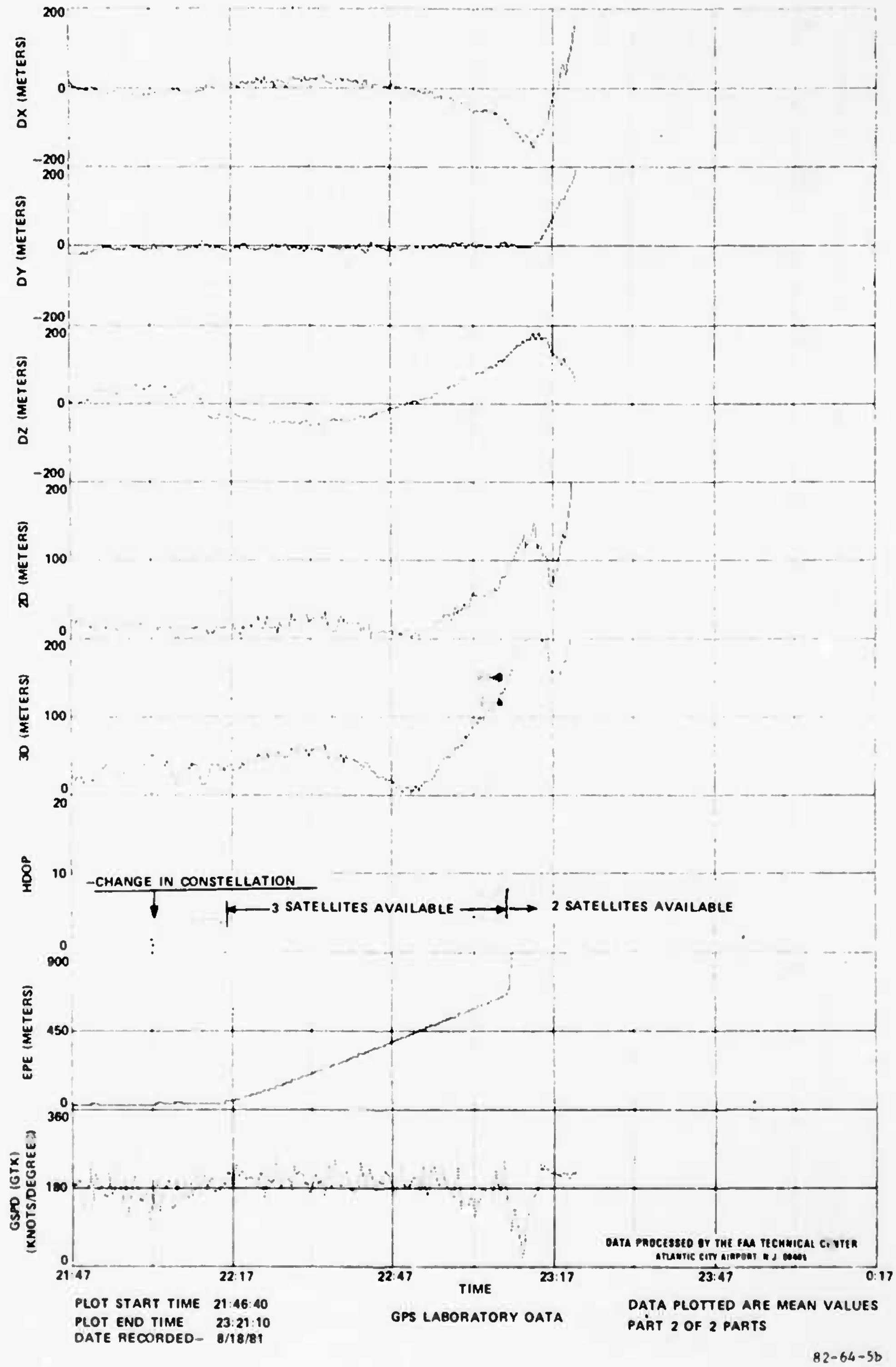
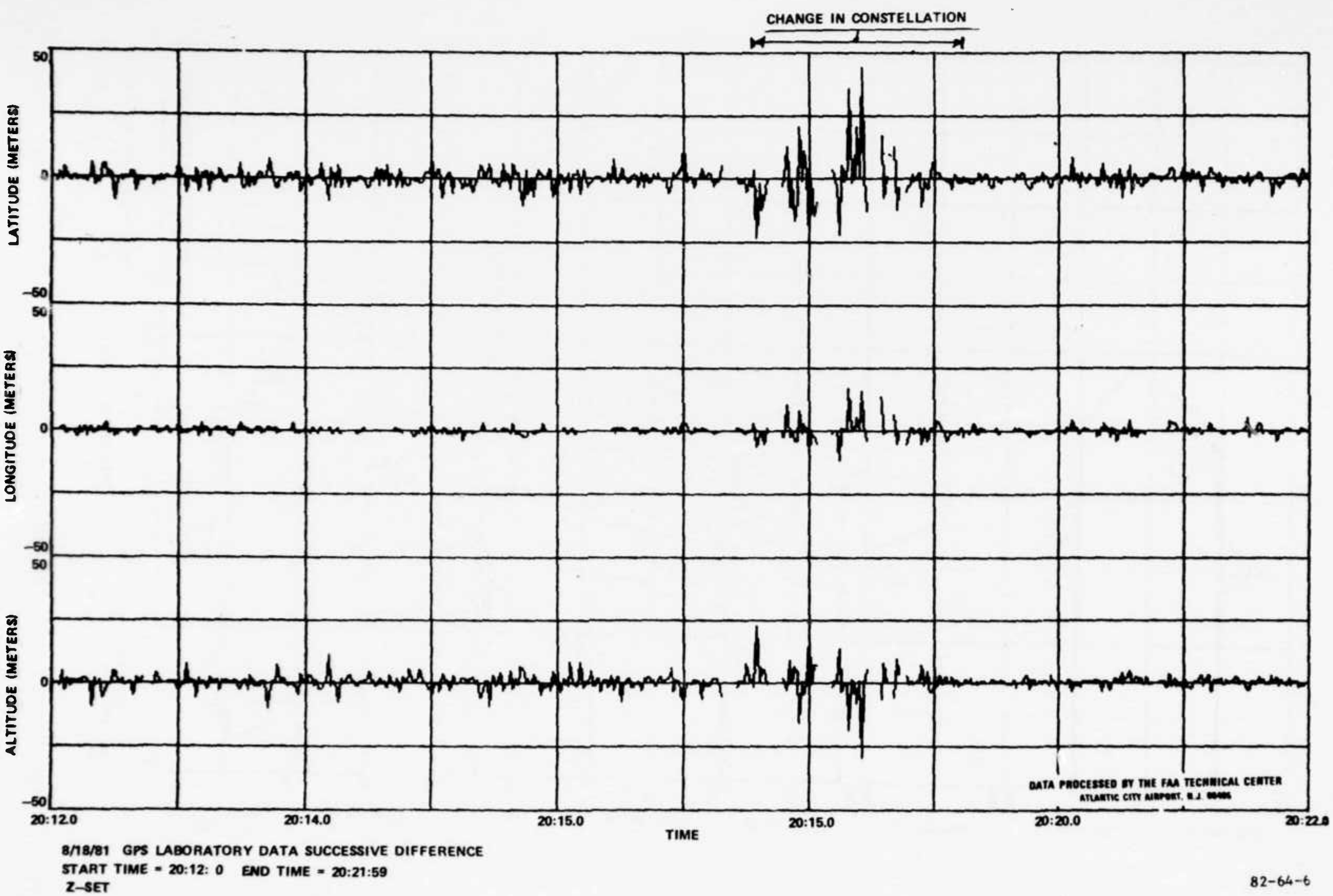


FIGURE 5. DELTA MEAN PLOT SHOWING CHANGE IN SATELLITE CONSTELLATION (SHEET 2 OF 2)



82-64-6

FIGURE 6. SUCCESSIVE DIFFERENCE PLOT SHOWING CHANGE IN SATELLITE CONSTELLATION ON AUGUST 18, 1981

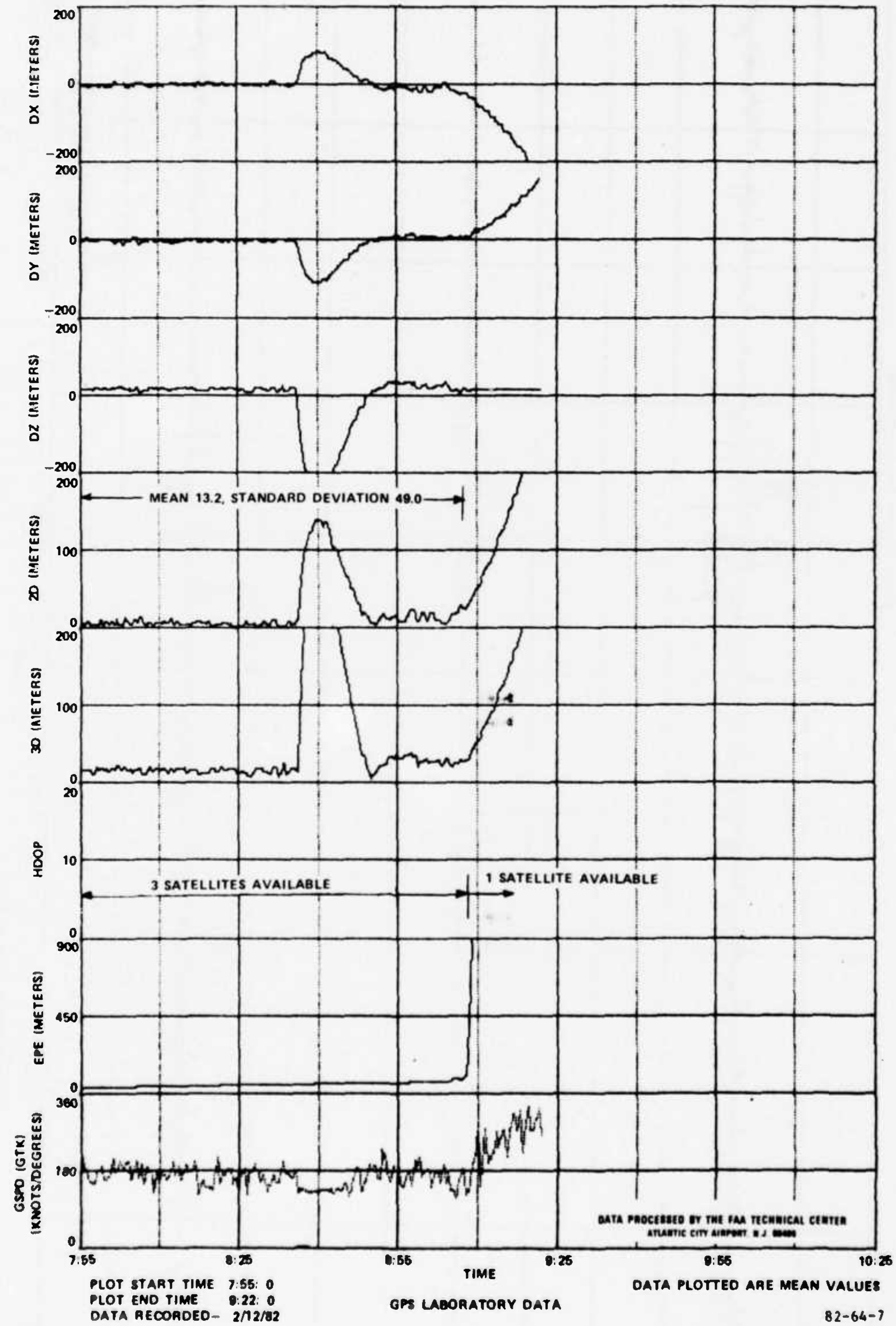
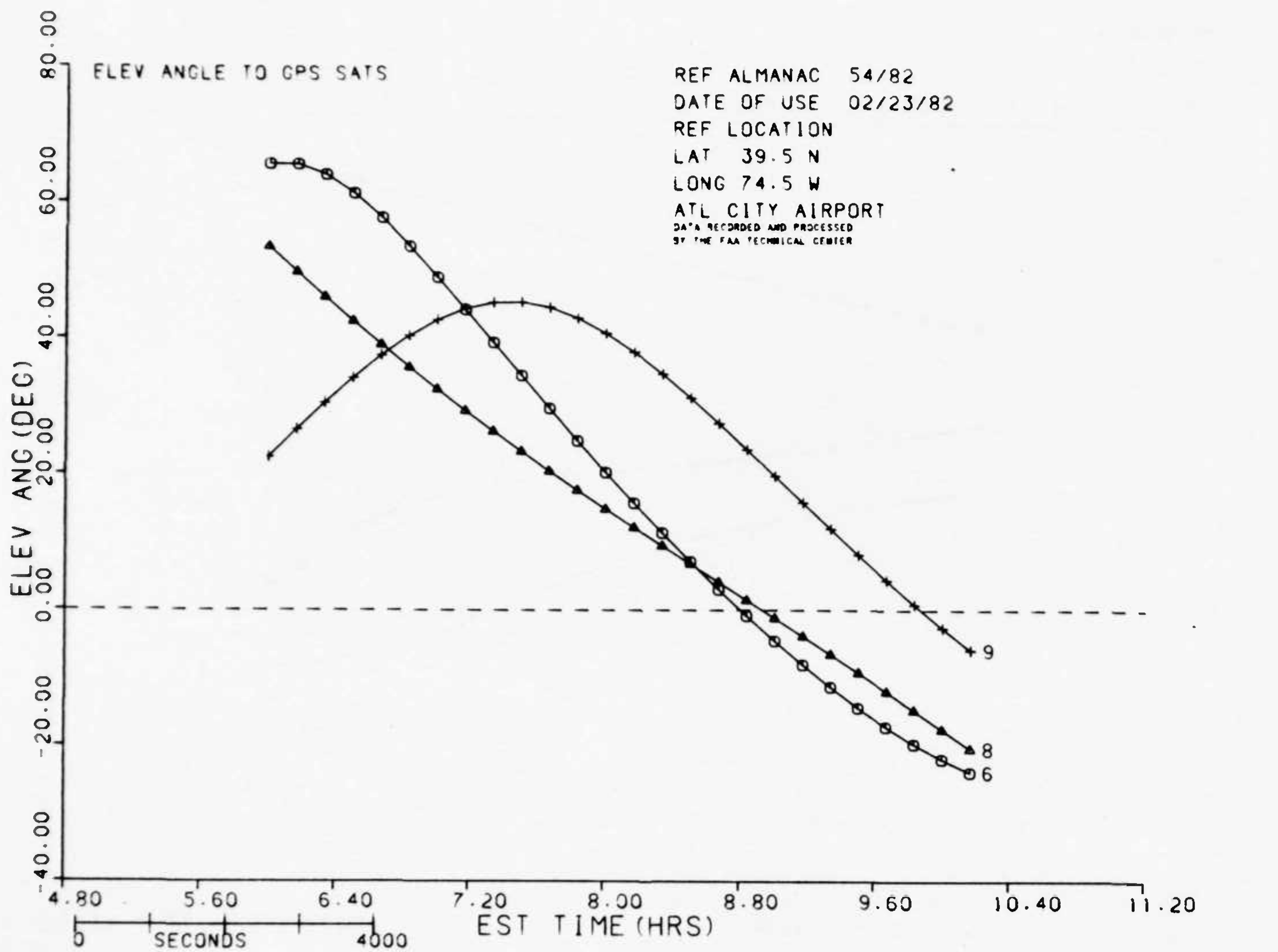
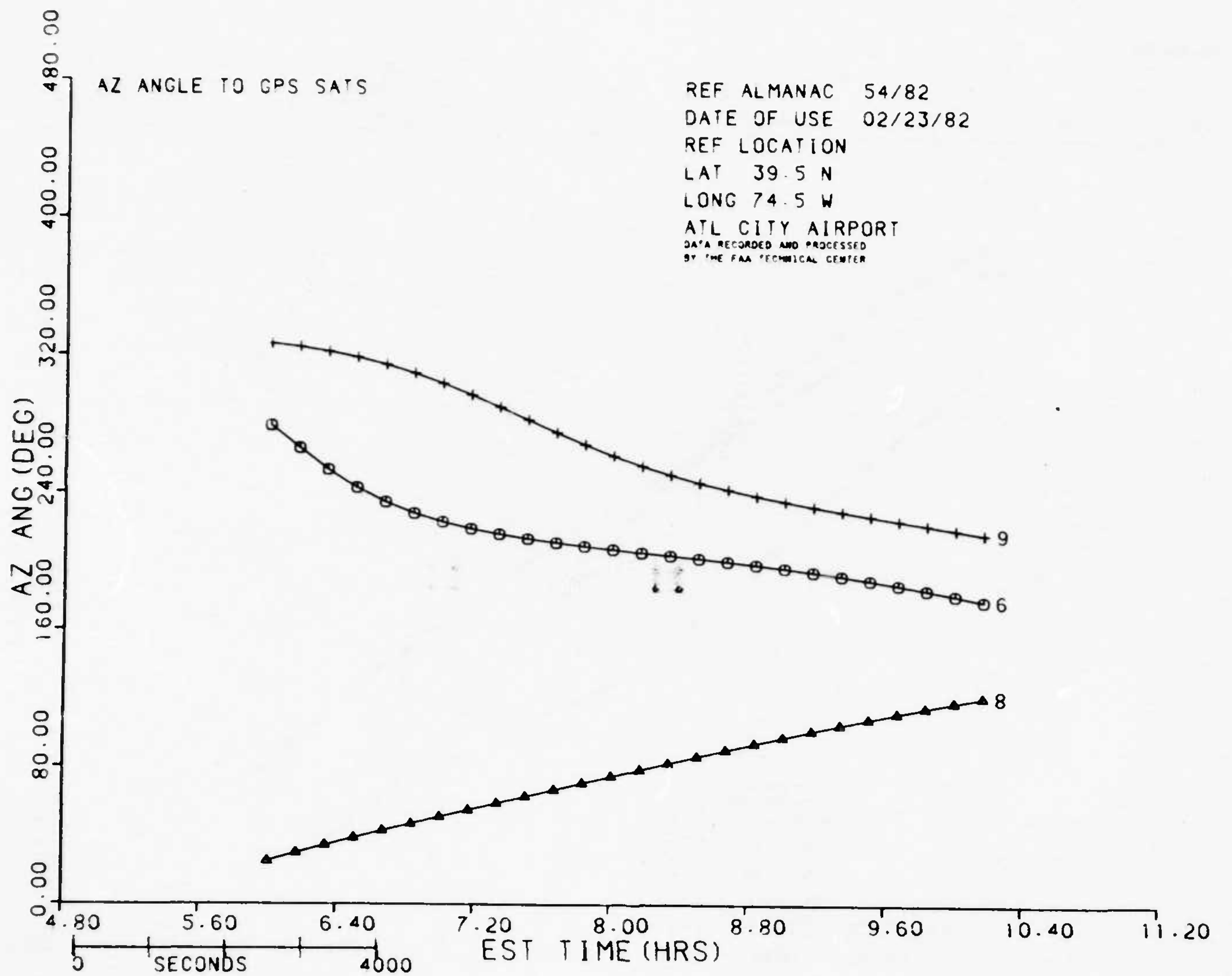


FIGURE 7. DELTA MEAN PLOT FOR NAVIGATION MODE WITHOUT CONTINUOUS ALTITUDE INPUT ON FEBRUARY 12, 1982



82-64-8a

FIGURE 8. SATELLITE PATH PLOT FOR NAVIGATION MODE TEST ON FEBRUARY 23, 1982 (SHEET 1 OF 2)



82-64-8b

FIGURE 8. SATELLITE PATH PLOT FOR NAVIGATION MODE TEST ON FEBRUARY 23, 1982 (SHEET 2 OF 2)

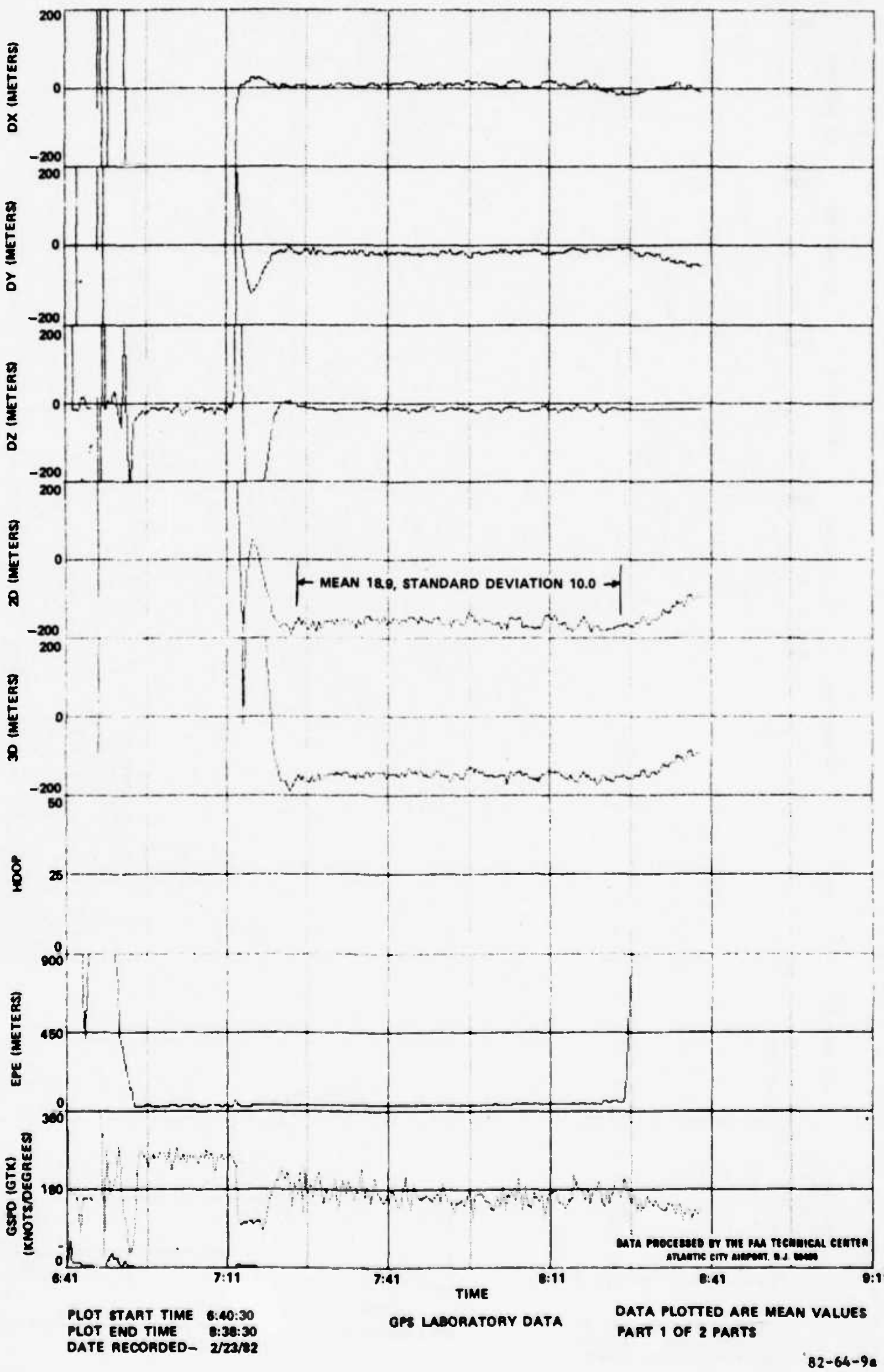


FIGURE 9. DELTA MEAN PLOT FOR NAVIGATION MODE WITH ALTIMETER ON FEBRUARY 23, 1982 (SHEET 1 OF 2)

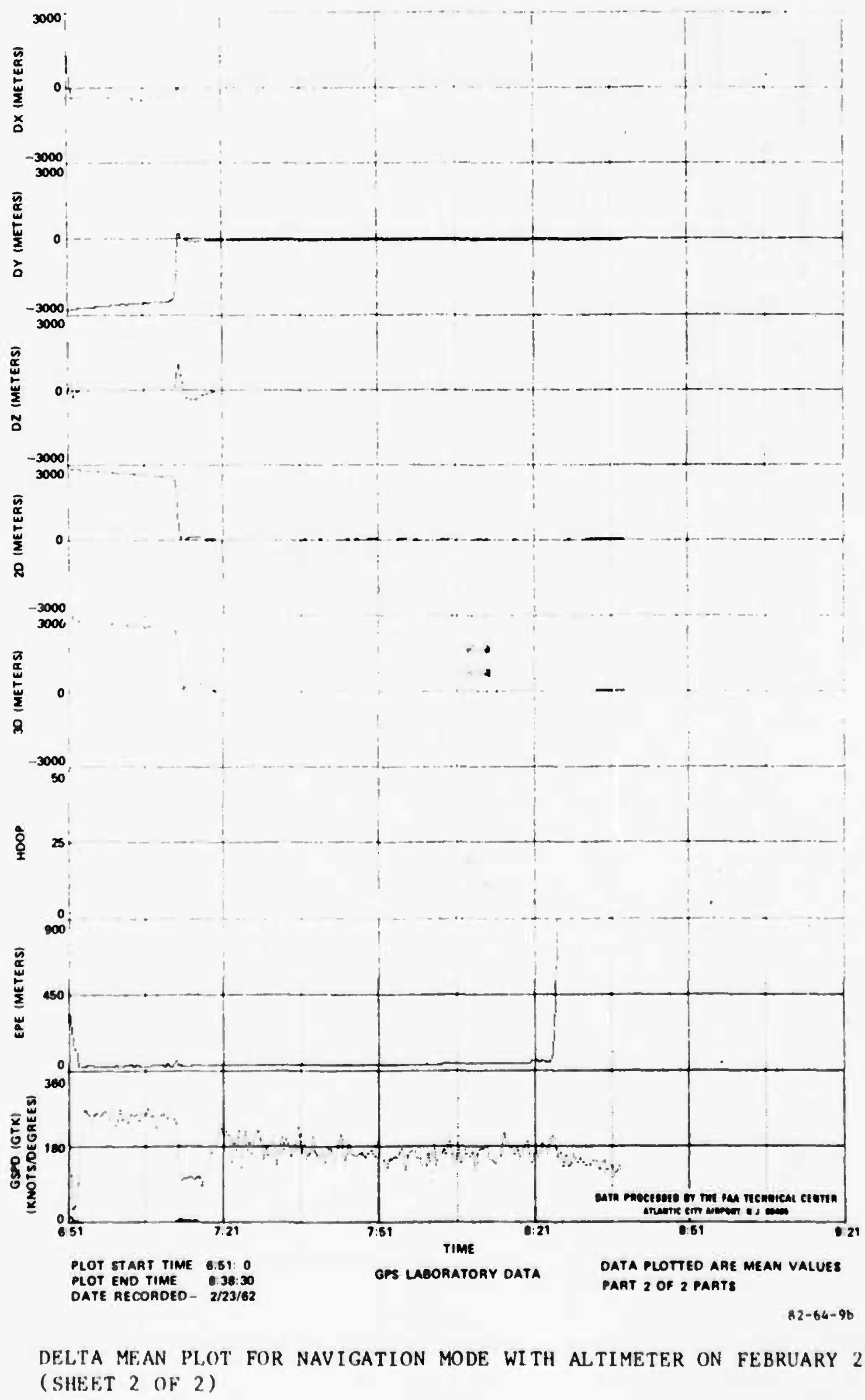


FIGURE 9. DELTA MEAN PLOT FOR NAVIGATION MODE WITH ALTIMETER ON FEBRUARY 23, 1982 (SHEET 2 OF 2)

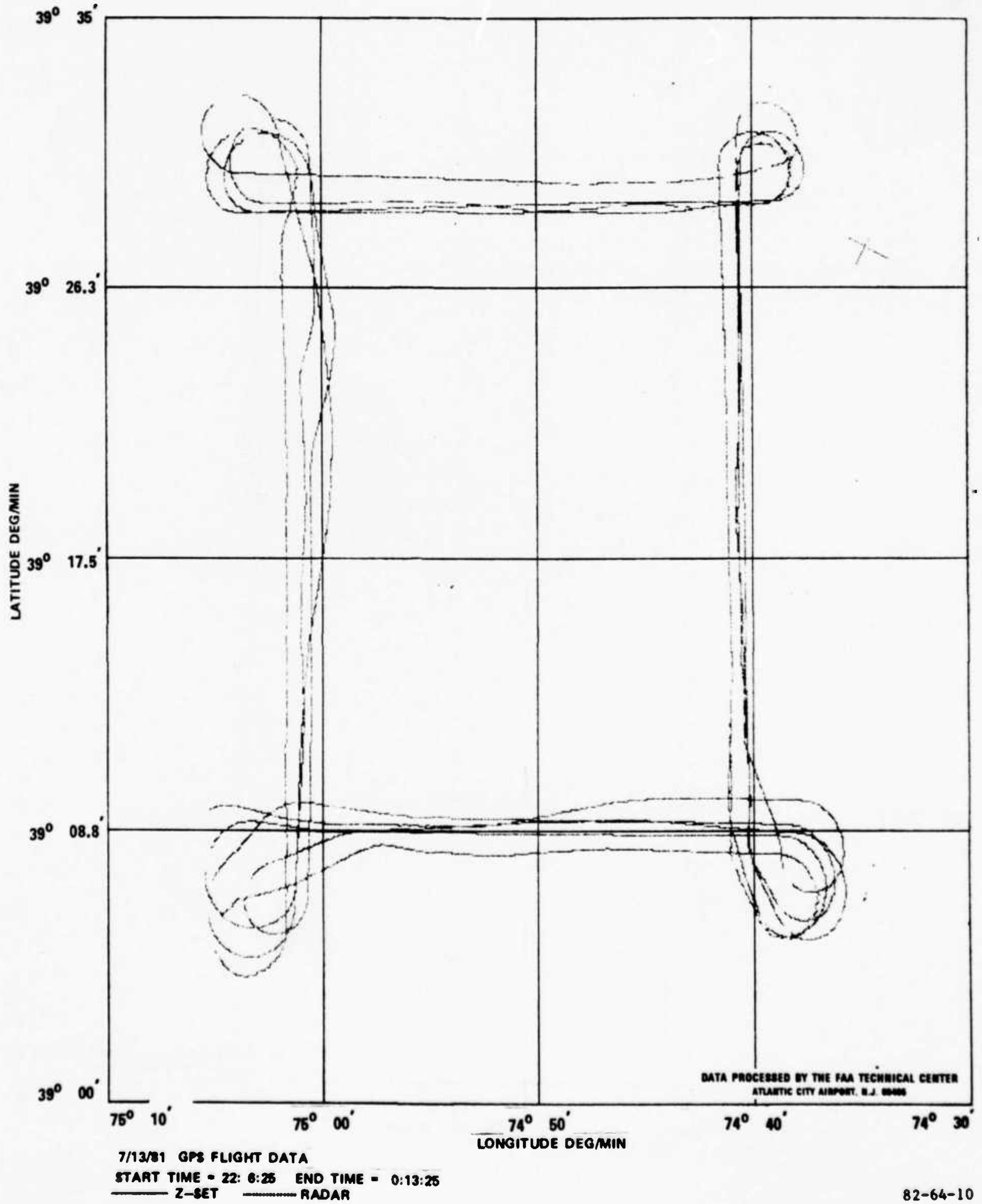


FIGURE 10. RADAR DETERMINED RECTAGULAR FLIGHTPATH ON JULY 13, 1981

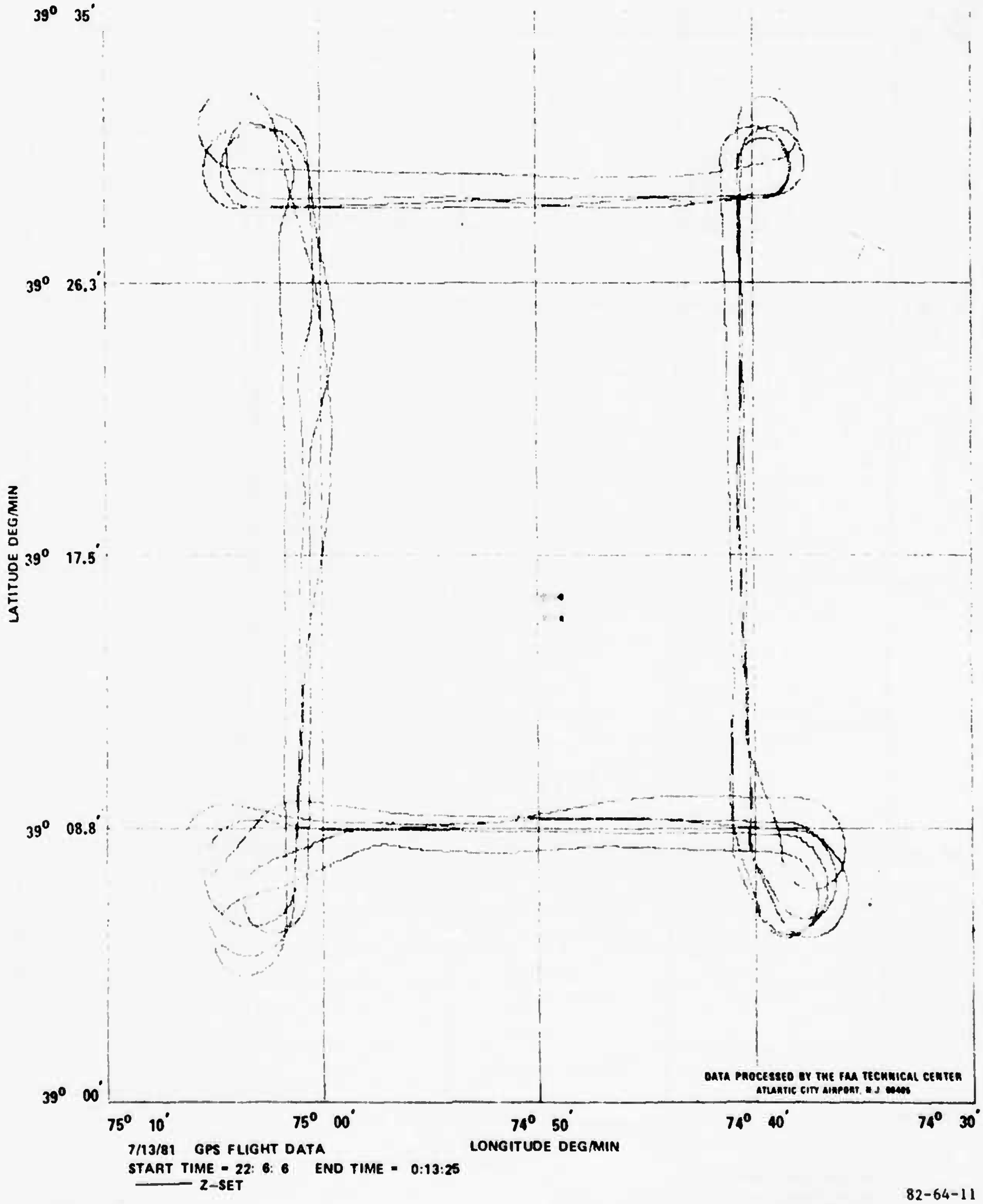


FIGURE 11. GPS DETERMINED FLIGHTPATH ON JULY 13, 1981

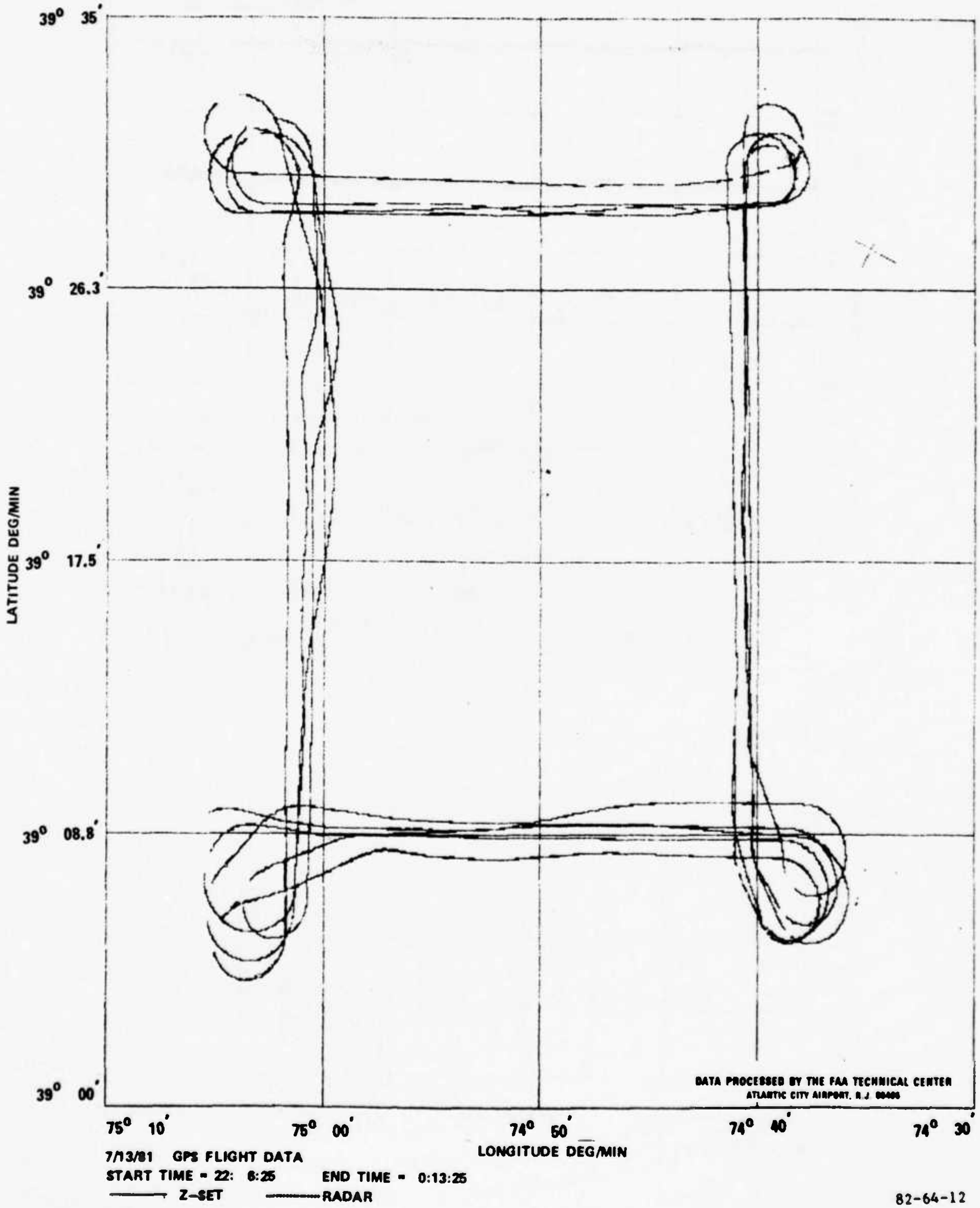


FIGURE 12. GPS AND RADAR DETERMINED FLIGHTPATH ON JULY 13, 1981

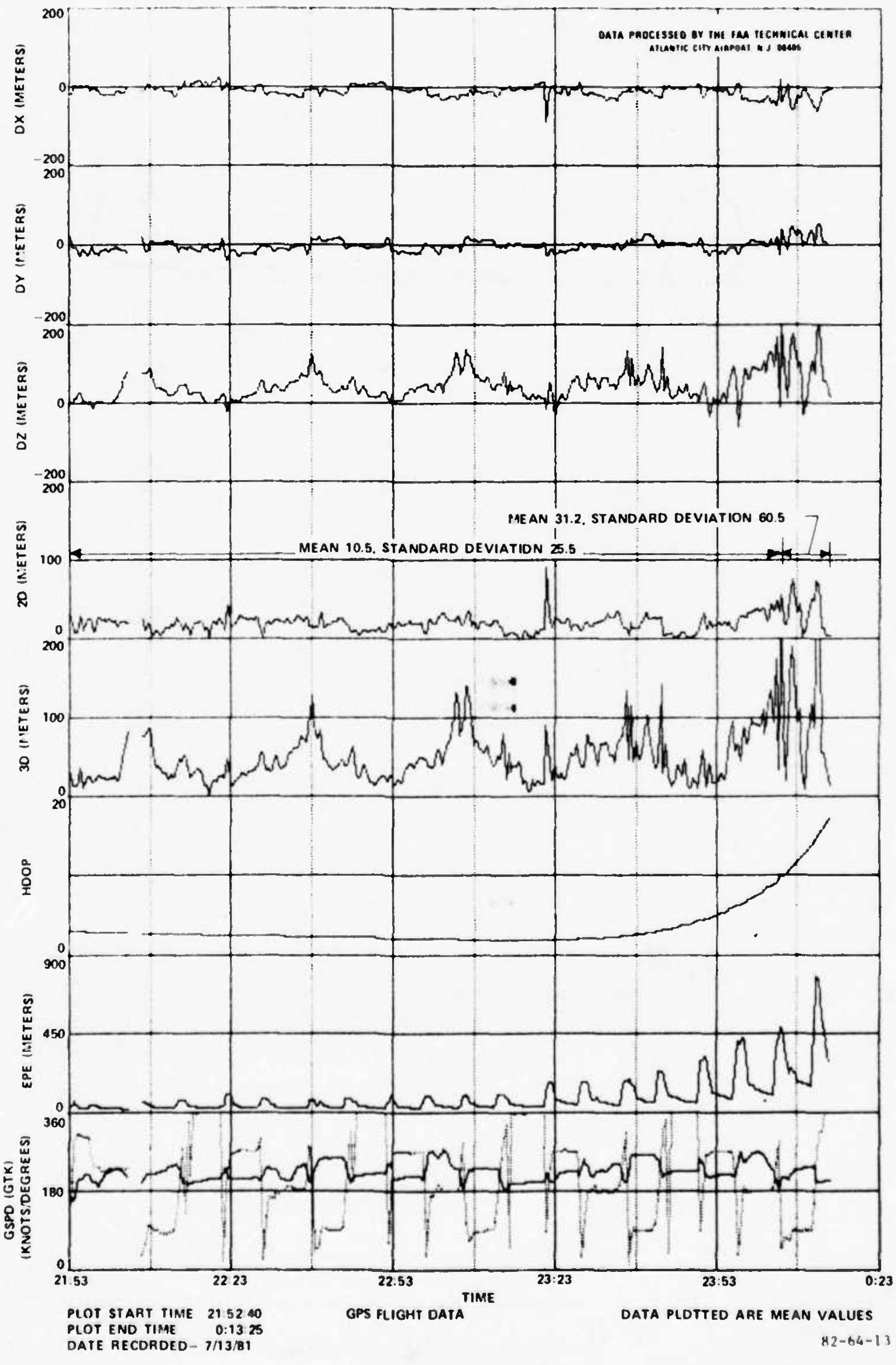


FIGURE 13. DELTA MEAN PLOT FOR RECTANGULAR FLIGHT ON JULY 13, 1981

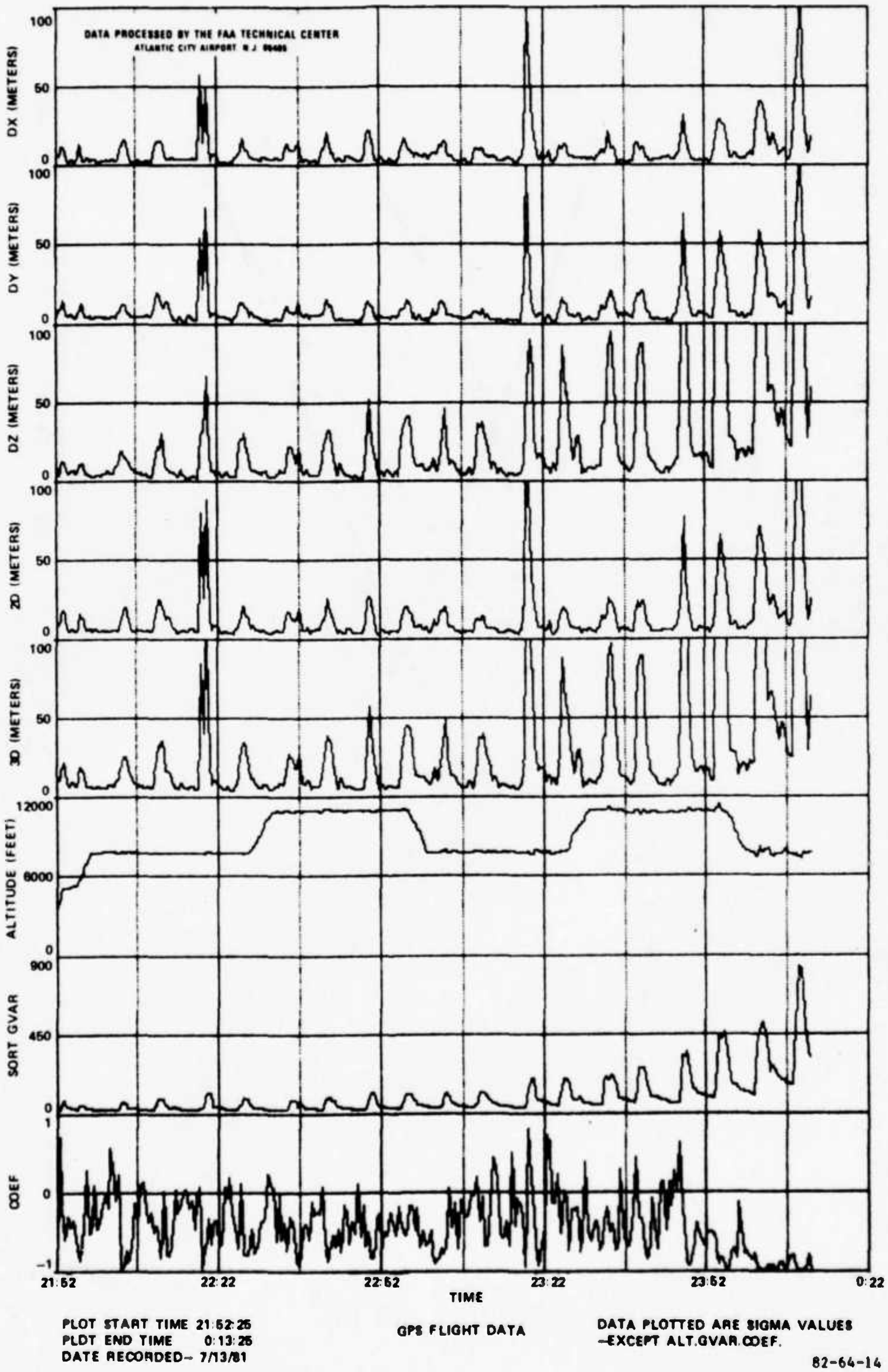


FIGURE 14. DELTA SIGMA PLOT FOR RECTANGULAR FLIGHT ON JULY 13, 1981

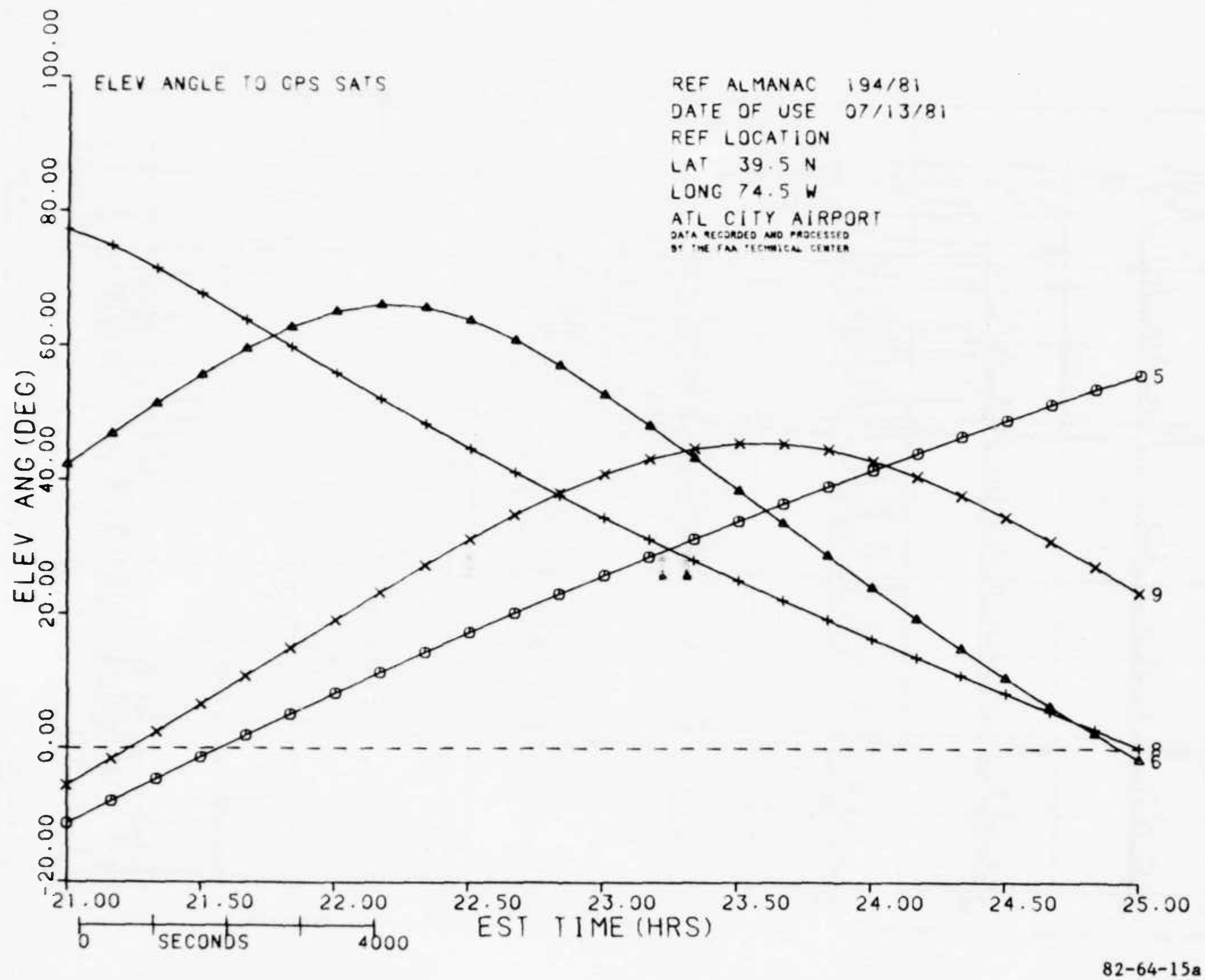


FIGURE 15. SATELLITE PATH PLOT FOR JULY 13, 1981 (SHEET 1 OF 2)

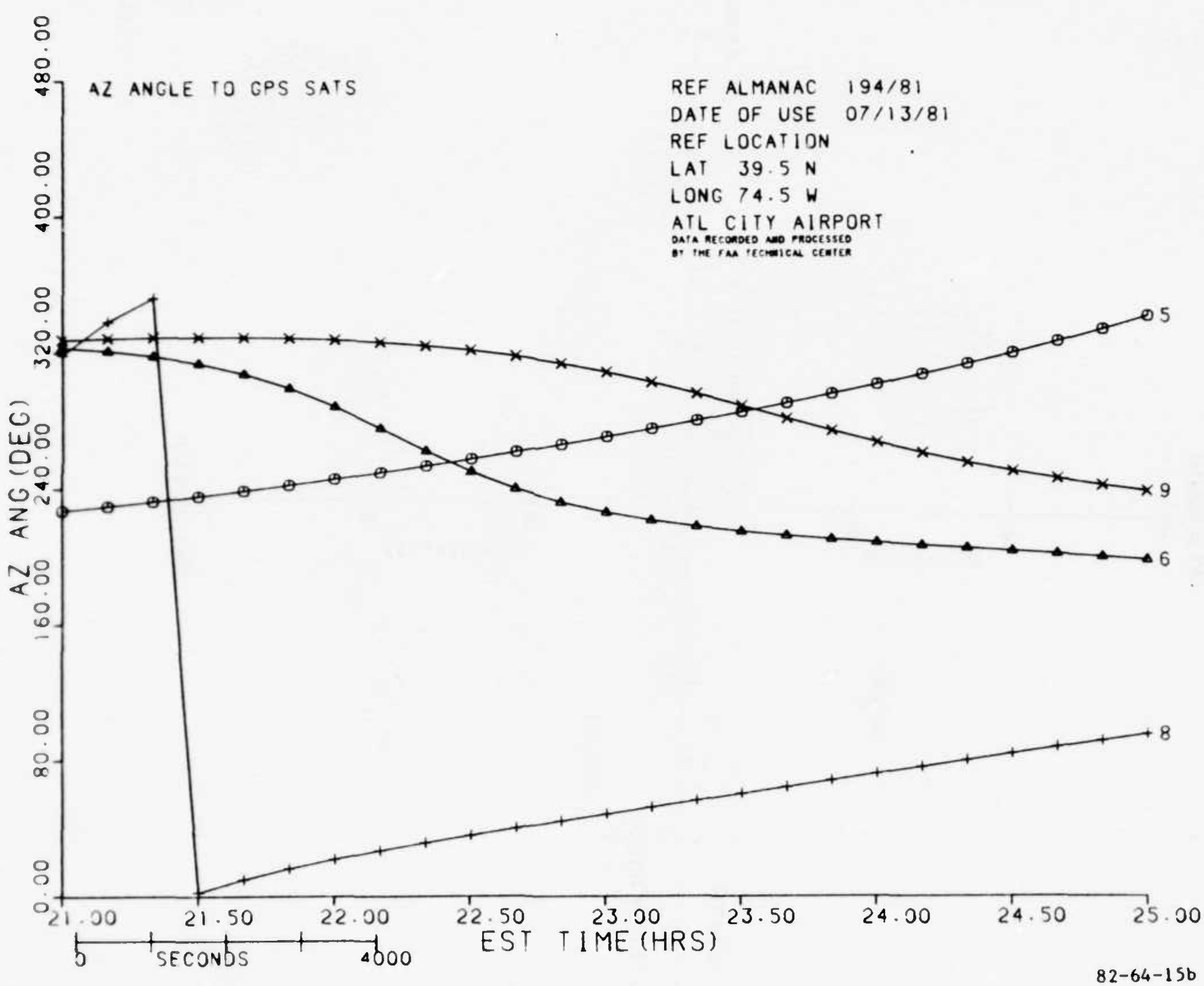


FIGURE 15. SATELLITE PATH PLOT FOR JULY 13, 1981 (SHEET 2 OF 2)

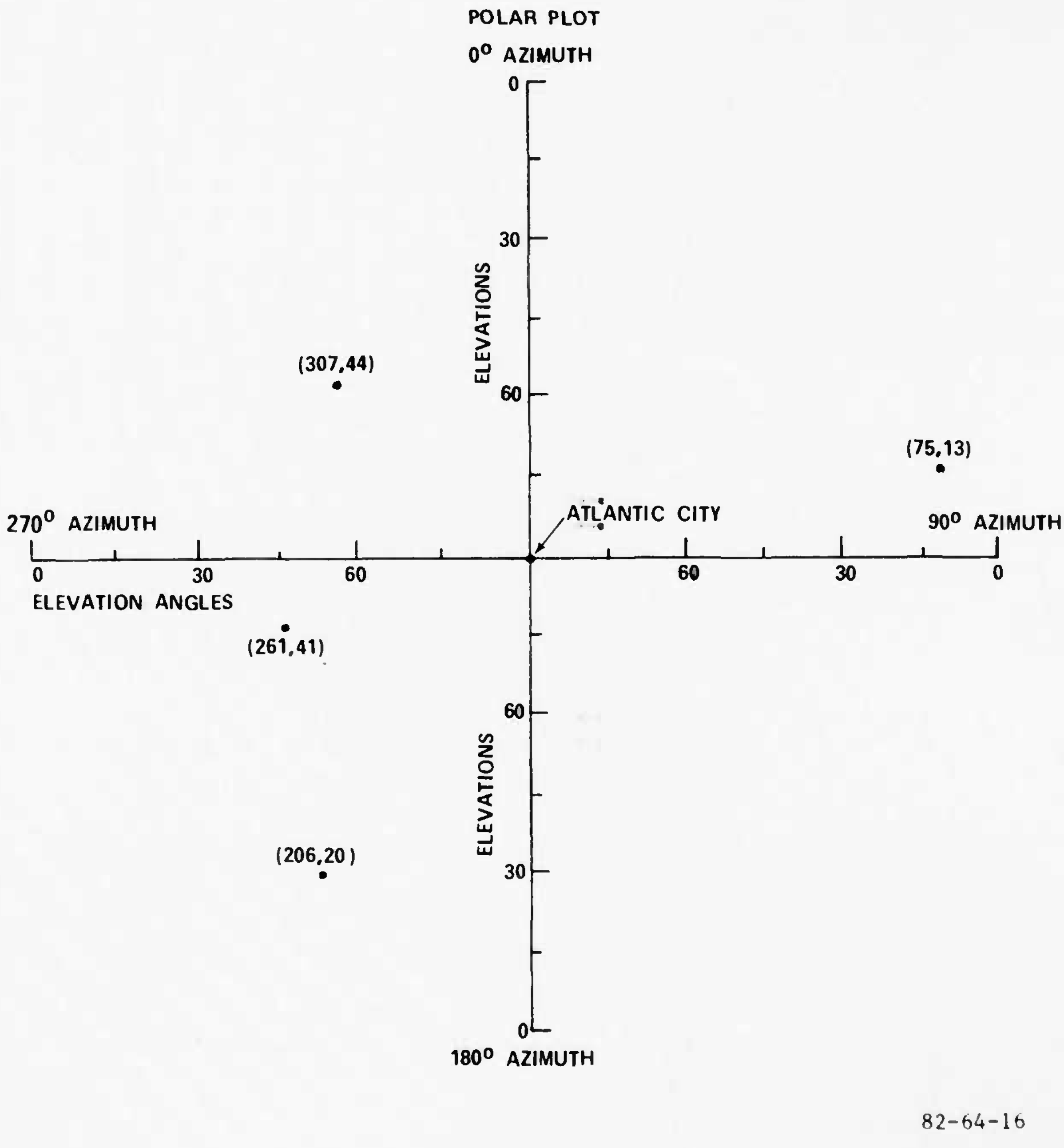


FIGURE 16. SATELLITE POSITION PLOT FOR HDOP=10

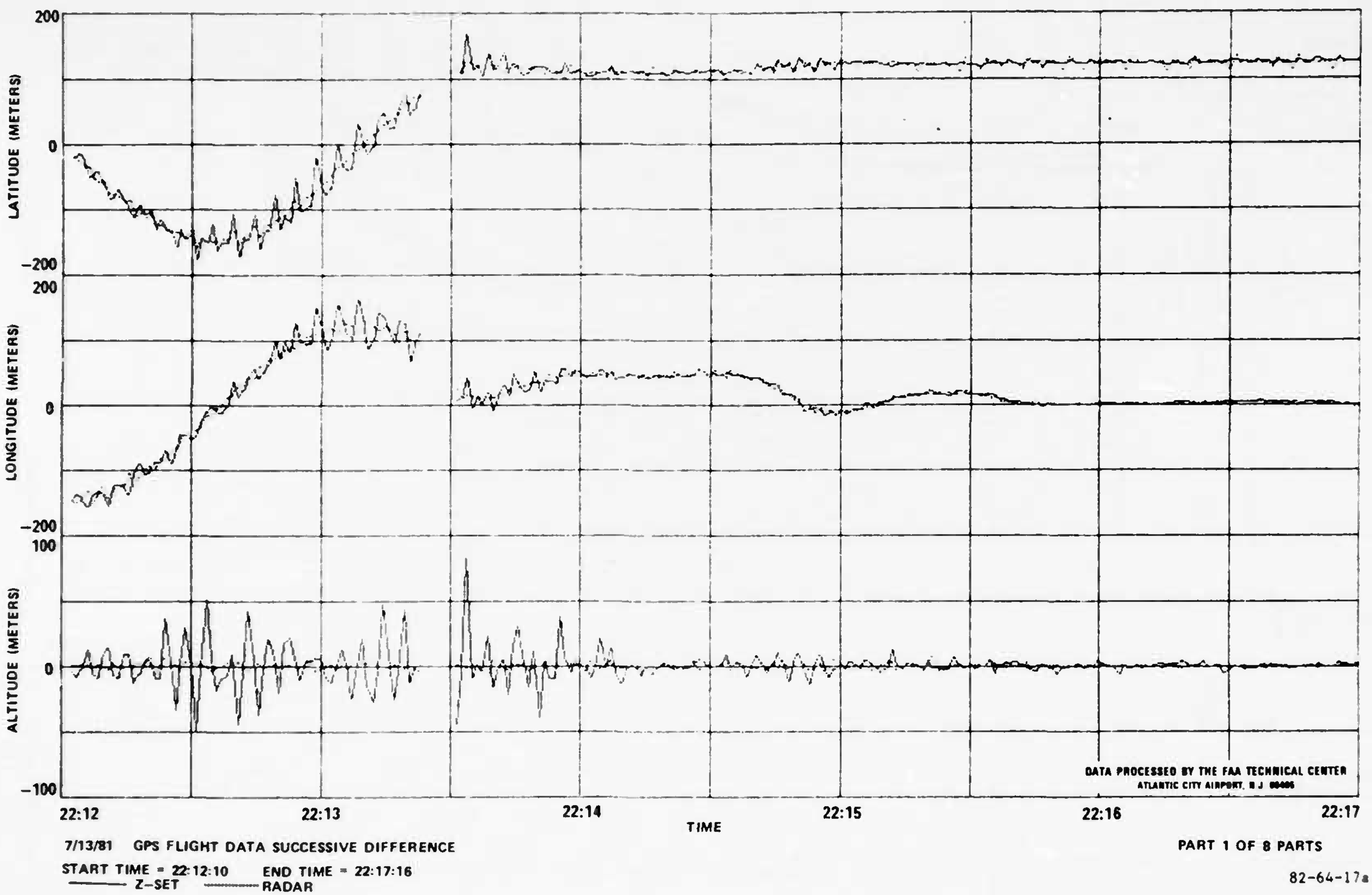


FIGURE 17. SUCCESSIVE DIFFERENCE PLOTS FOR JULY 13, 1981 (SHEET 1 OF 8)

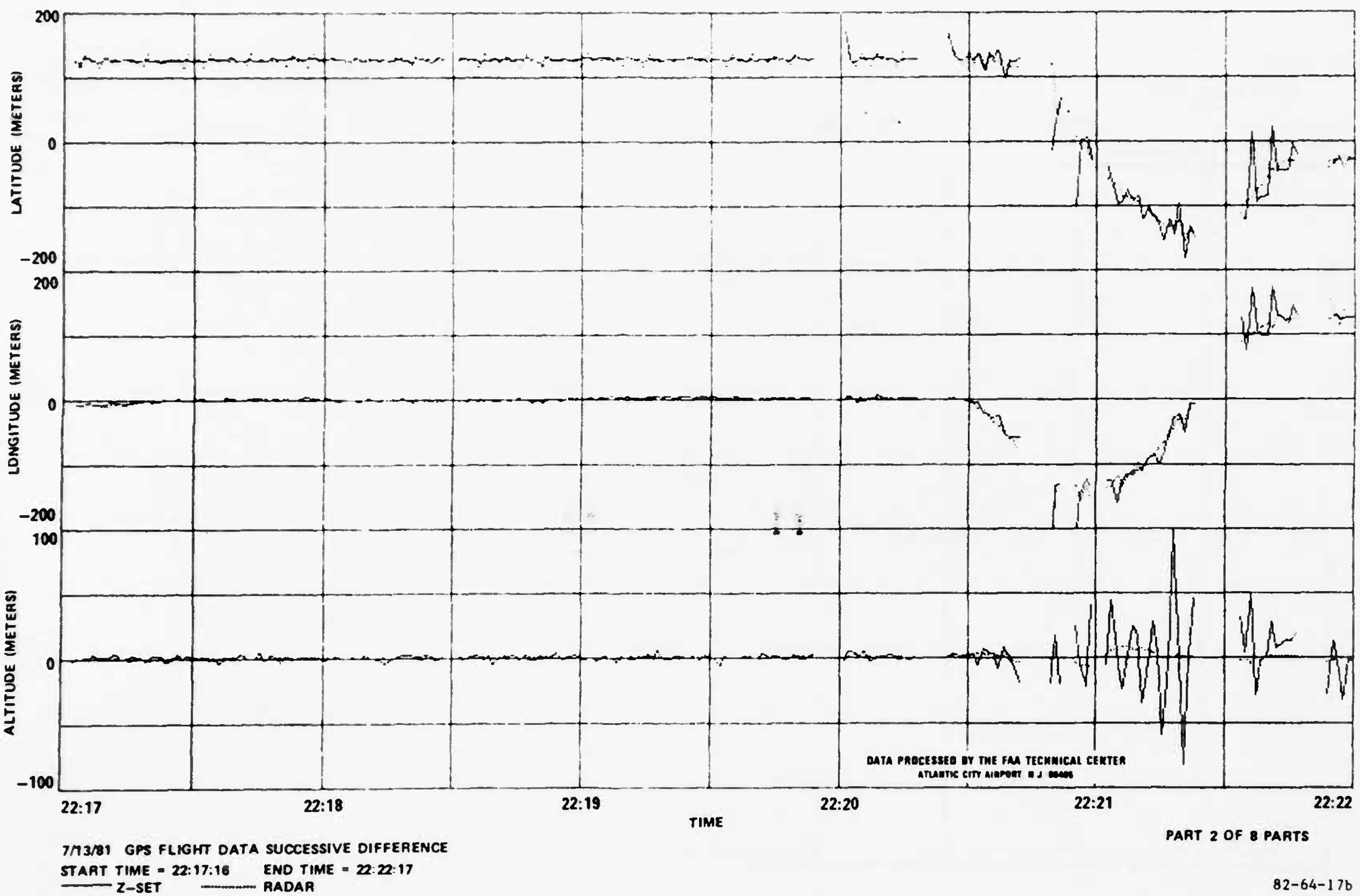
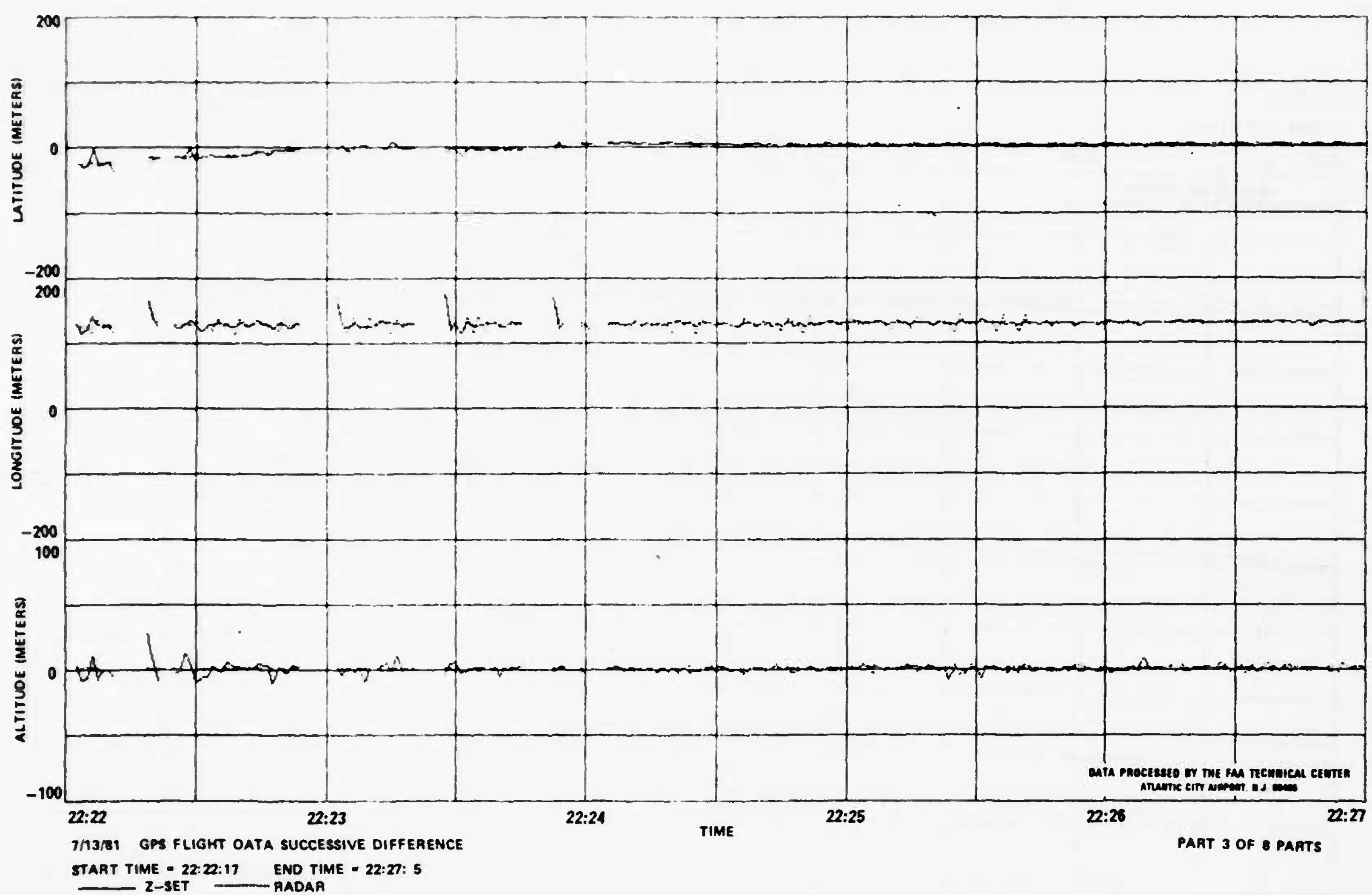


FIGURE 17. SUCCESSIVE DIFFERENCE PLOTS FOR JULY 13, 1981 (SHEET 2 OF 8)



82-64-17c

FIGURE 17. SUCCESSIVE DIFFERENCE PLOTS FOR JULY 13, 1981 (SHEET 3 OF 8)

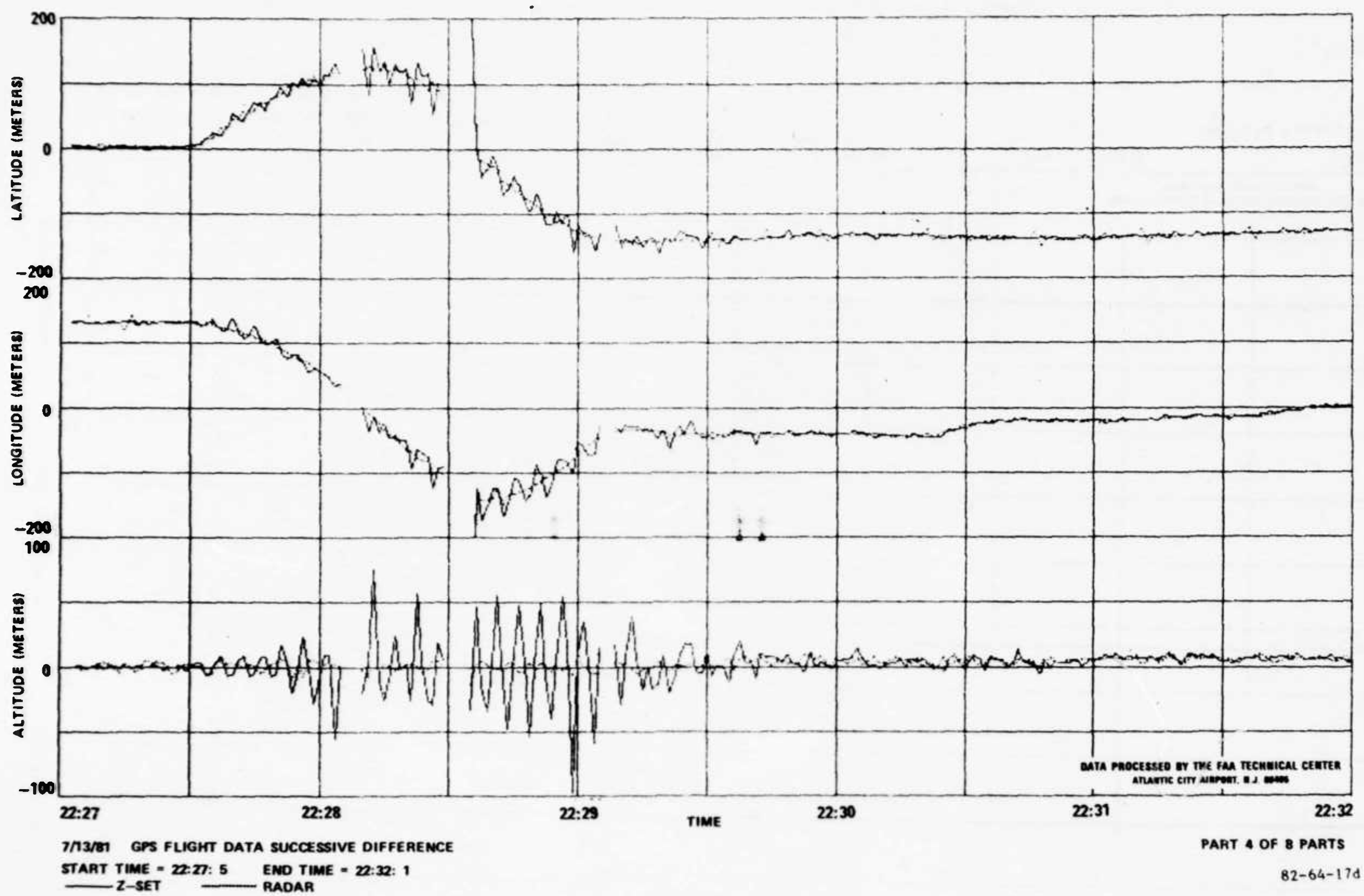
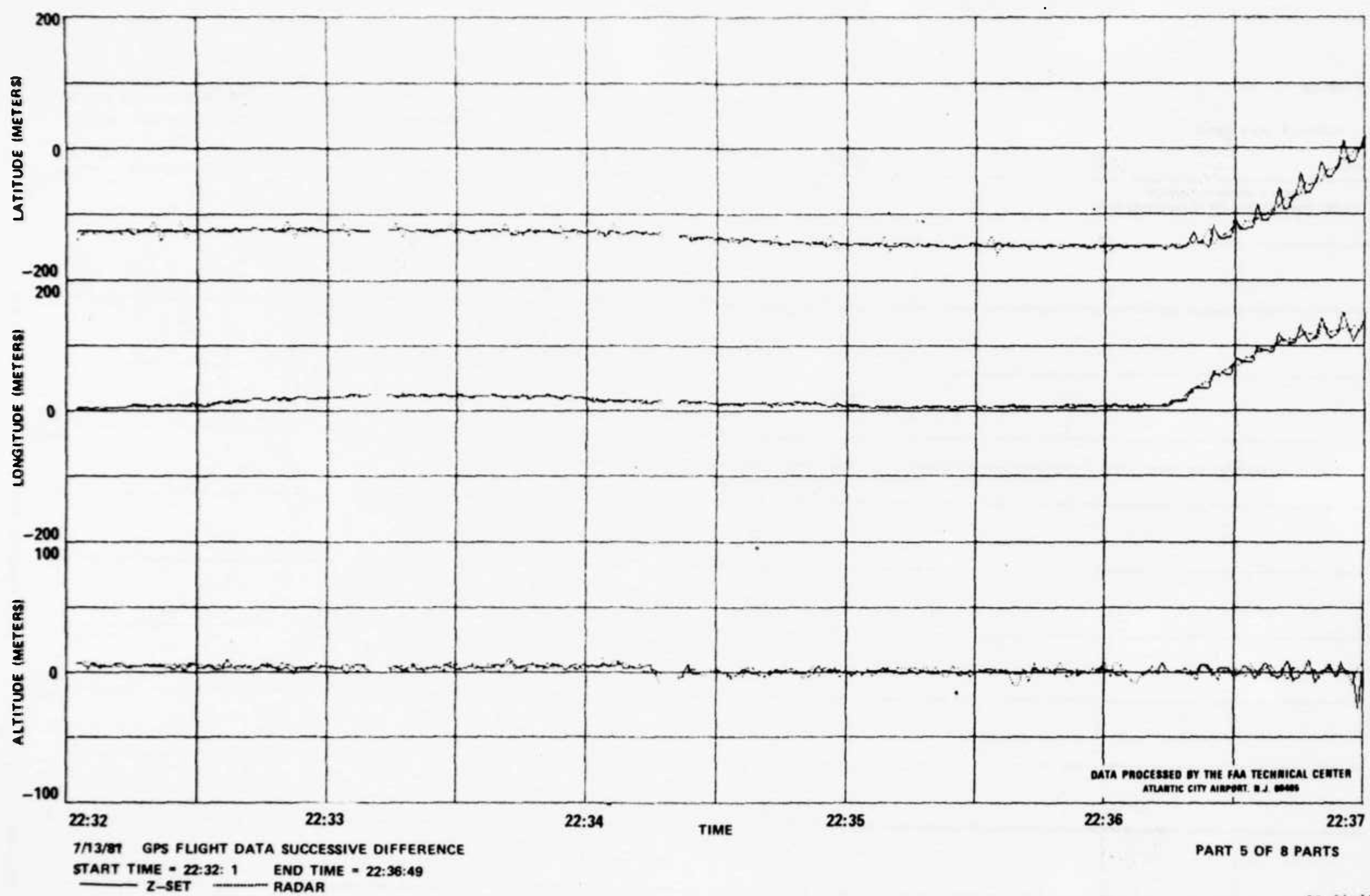


FIGURE 17. SUCCESSIVE DIFFERENCE PLOTS FOR JULY 13, 1981 (SHEET 4 OF 8)



82-64-17e

FIGURE 17. SUCCESSIVE DIFFERENCE PLOTS FOR JULY 13, 1981 (SHEET 5 OF 8)

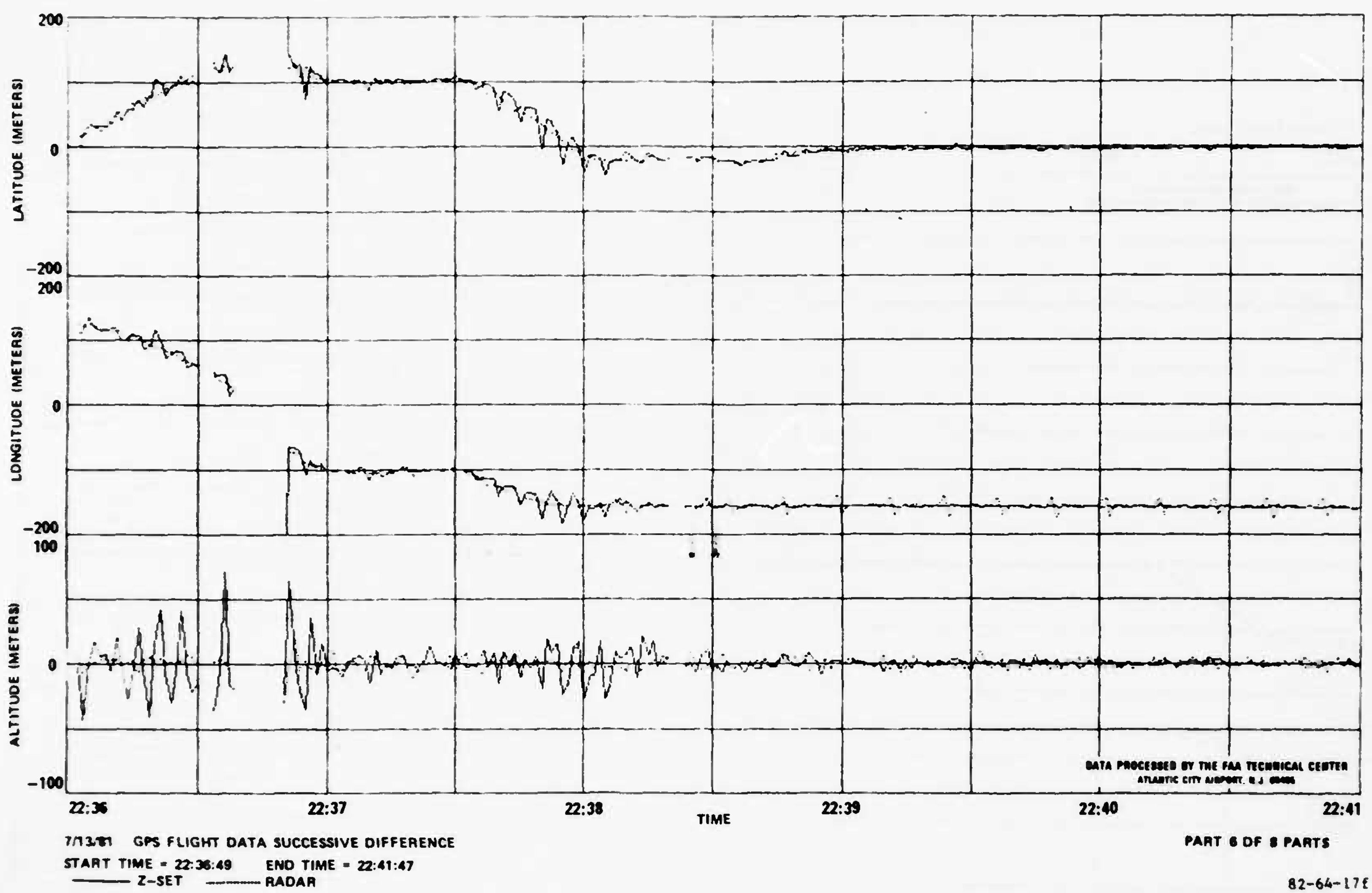


FIGURE 17. SUCCESSIVE DIFFERENCE PLOTS FOR JULY 13, 1981 (SHEET 6 OF 8)

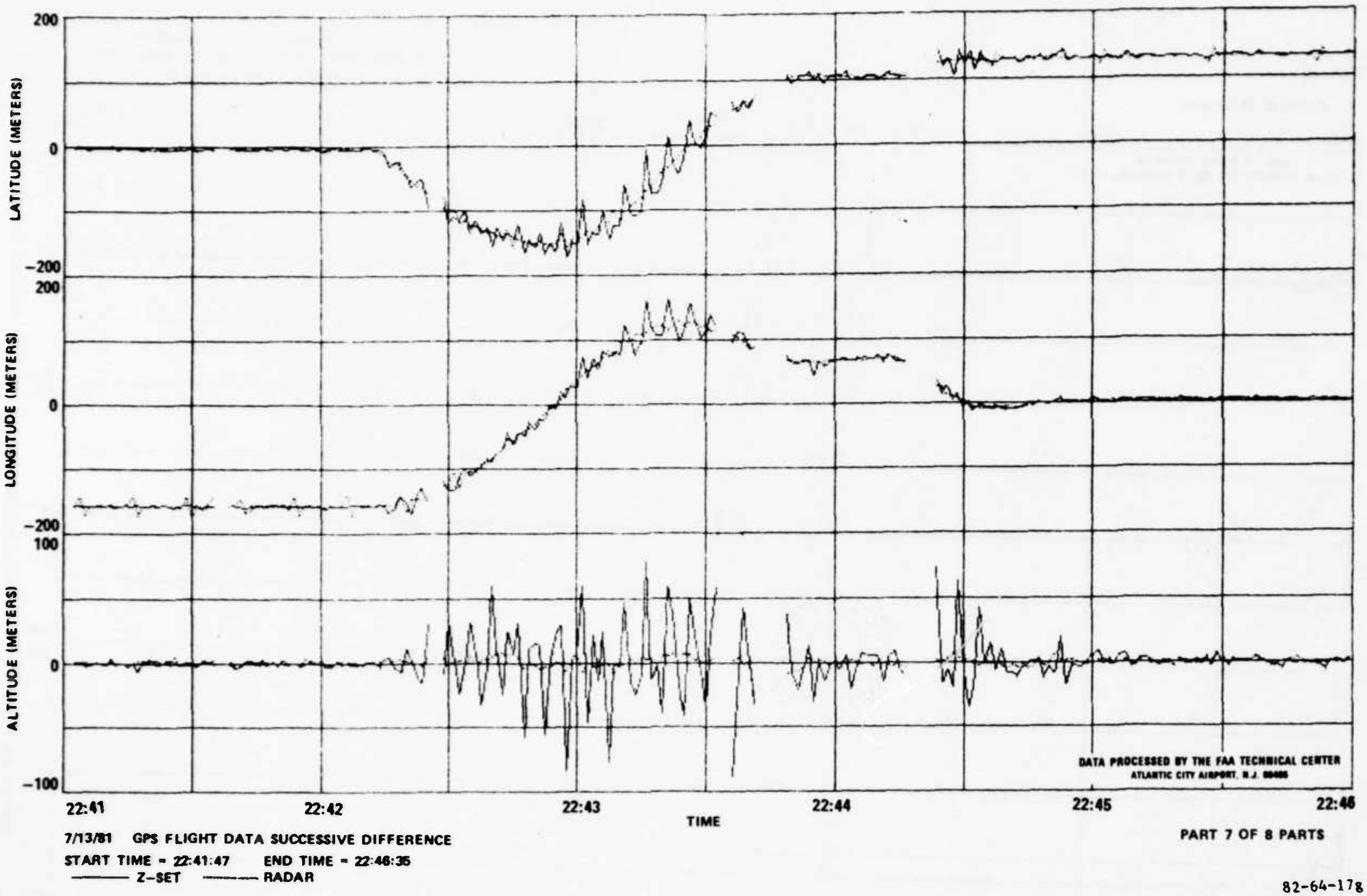


FIGURE 17. SUCCESSIVE DIFFERENCE PLOTS FOR JULY 13, 1981 (SHEET 7 OF 8)

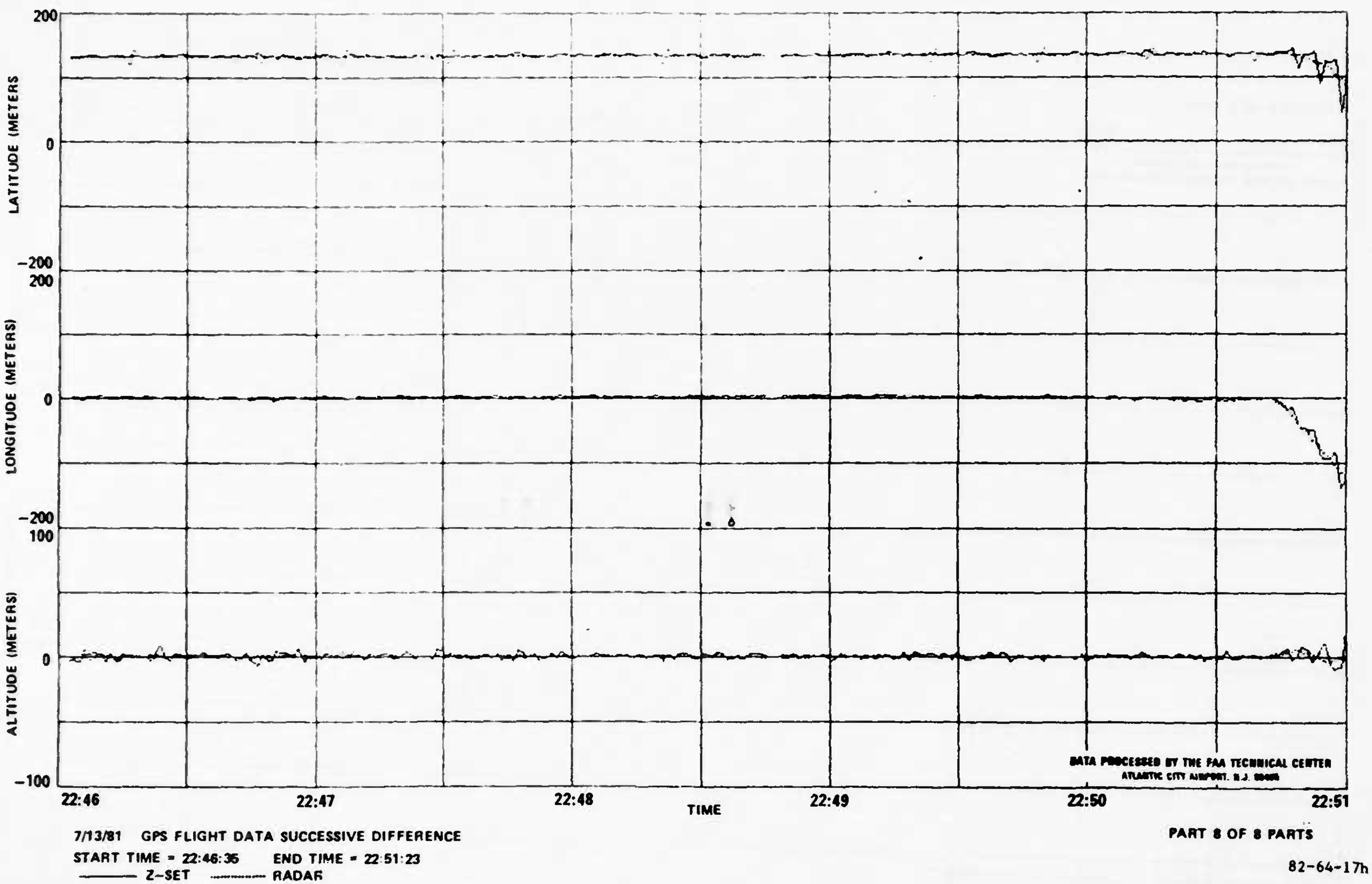
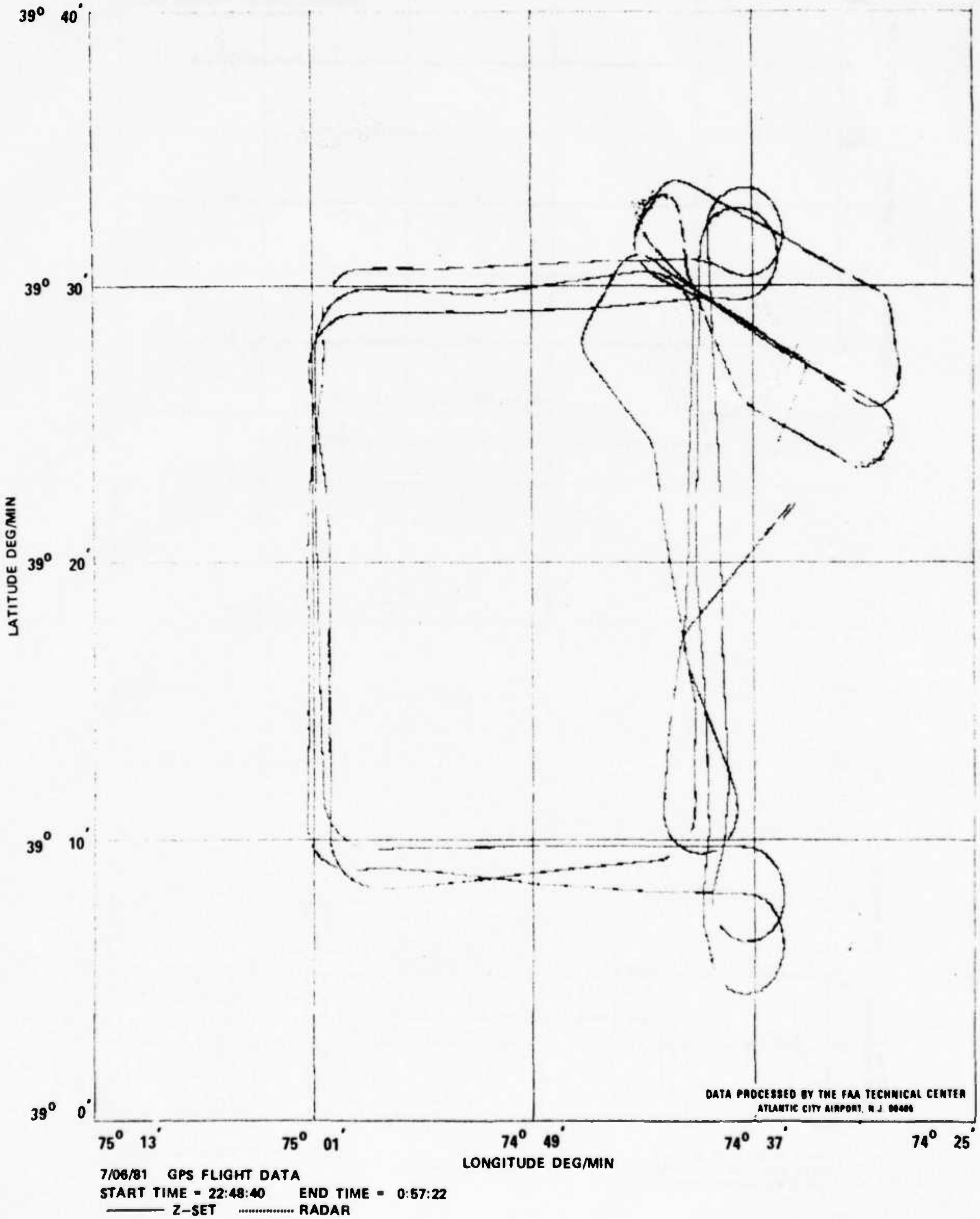


FIGURE 17. SUCCESSIVE DIFFERENCE PLOTS FOR JULY 13, 1981 (SHEET 8 OF 8)



82-64-18

FIGURE 18. GPS AND RADAR FLIGHT RECTANGULAR PATH FOR JULY 6, 1981

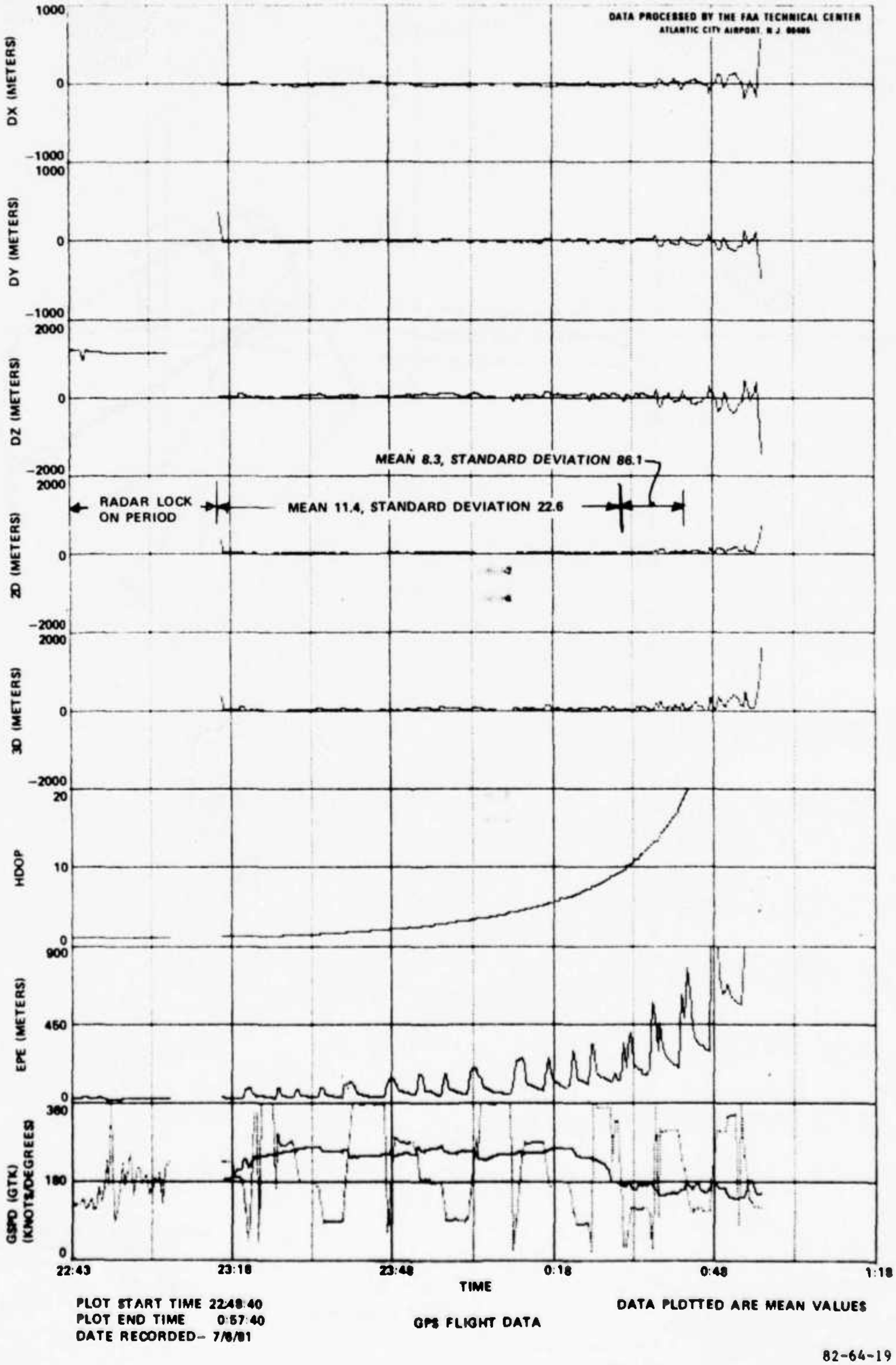
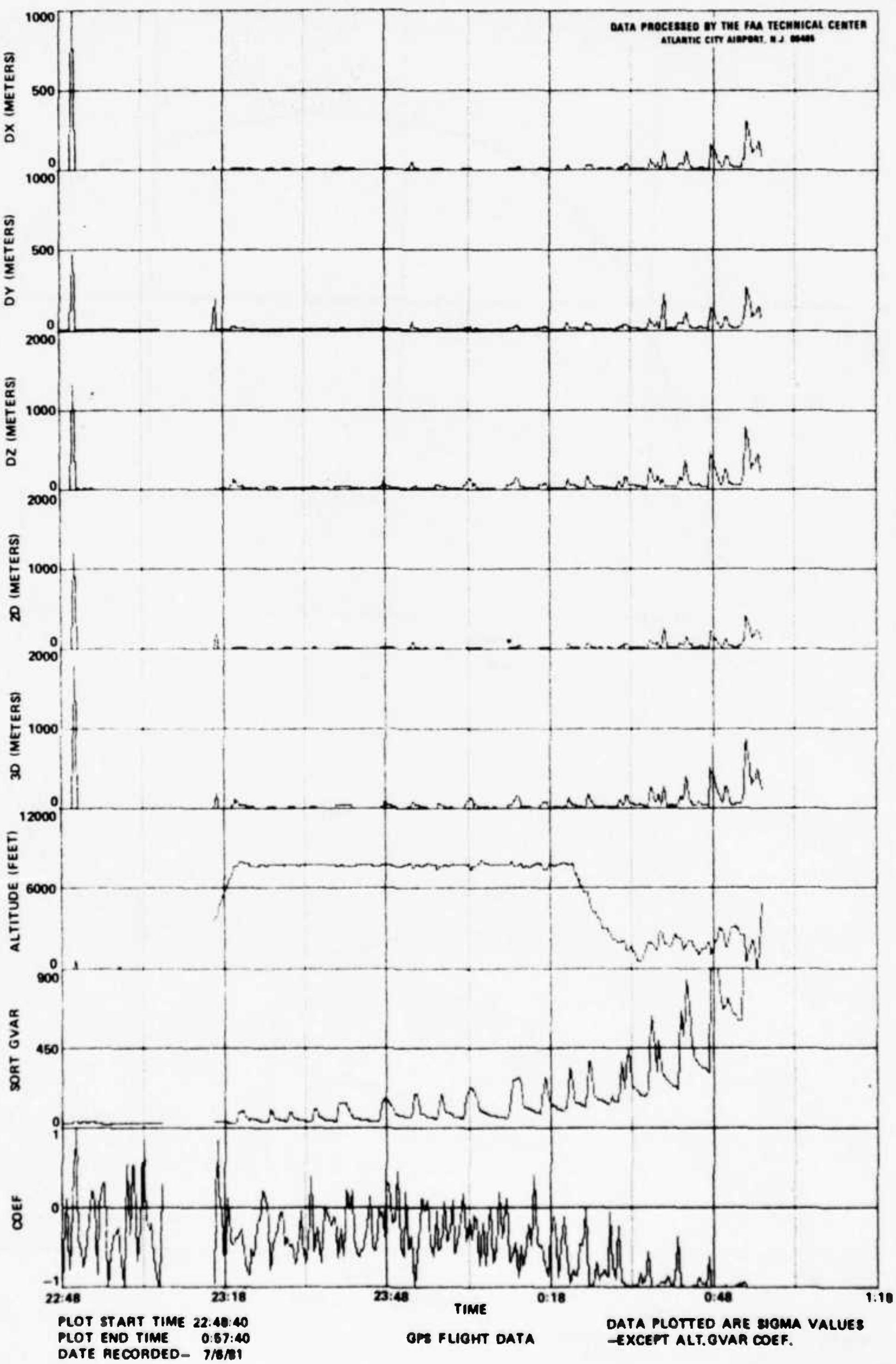
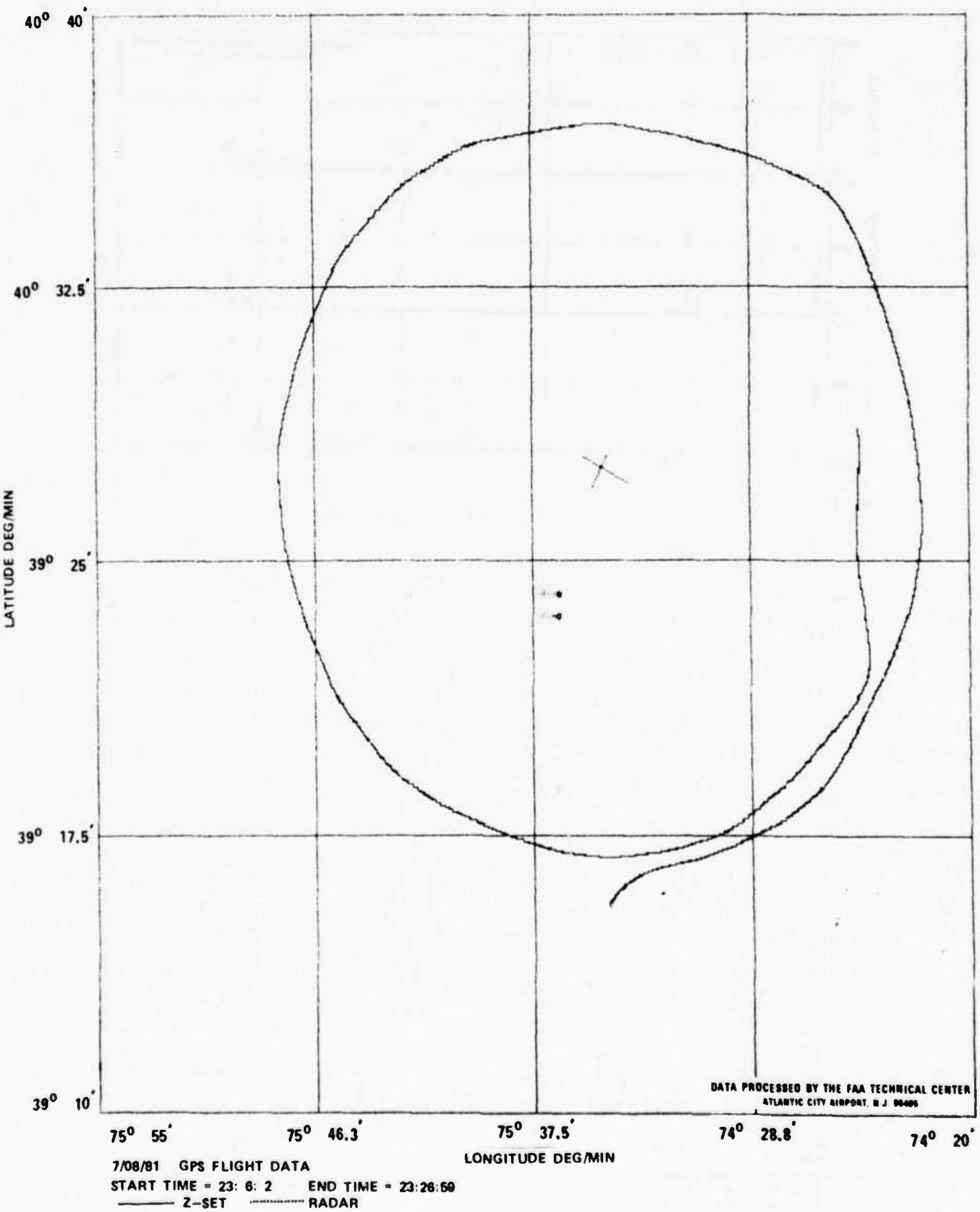


FIGURE 19. DELTA MEAN PLOT FOR JULY 6, 1981



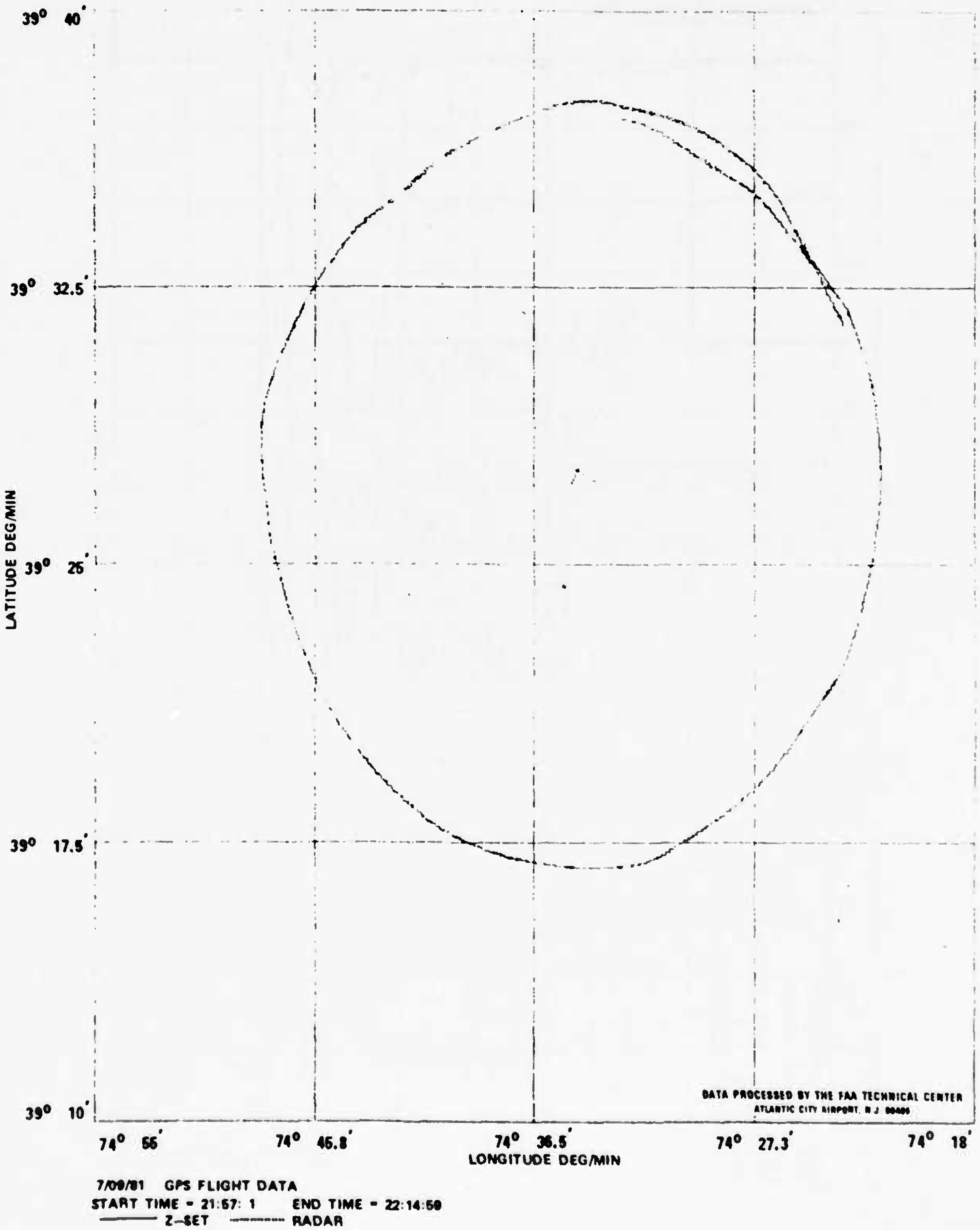
82-64-20

FIGURE 20. DELTA SIGMA PLOT FOR JULY 6, 1981



82-64-21

FIGURE 21. GPS AND RADAR DETERMINED ORBIT FLIGHTPATH ON JULY 8, 1981



82-64-22

FIGURE 22. GPS AND RADAR DETERMINED ORBIT FLIGHTPATH ON JULY 9, 1981

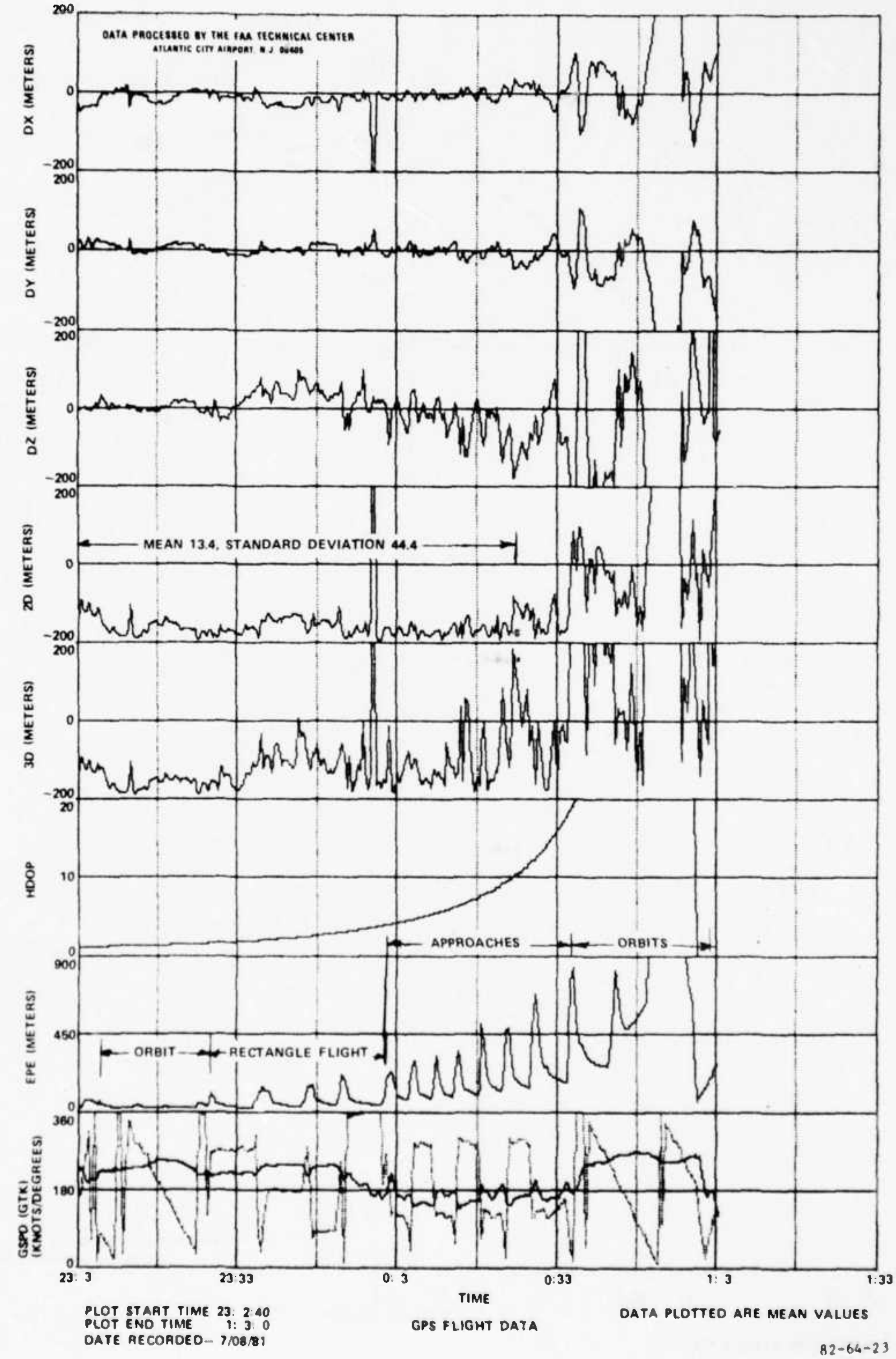


FIGURE 23. DELTA MEAN PLOT FOR JULY 8, 1981

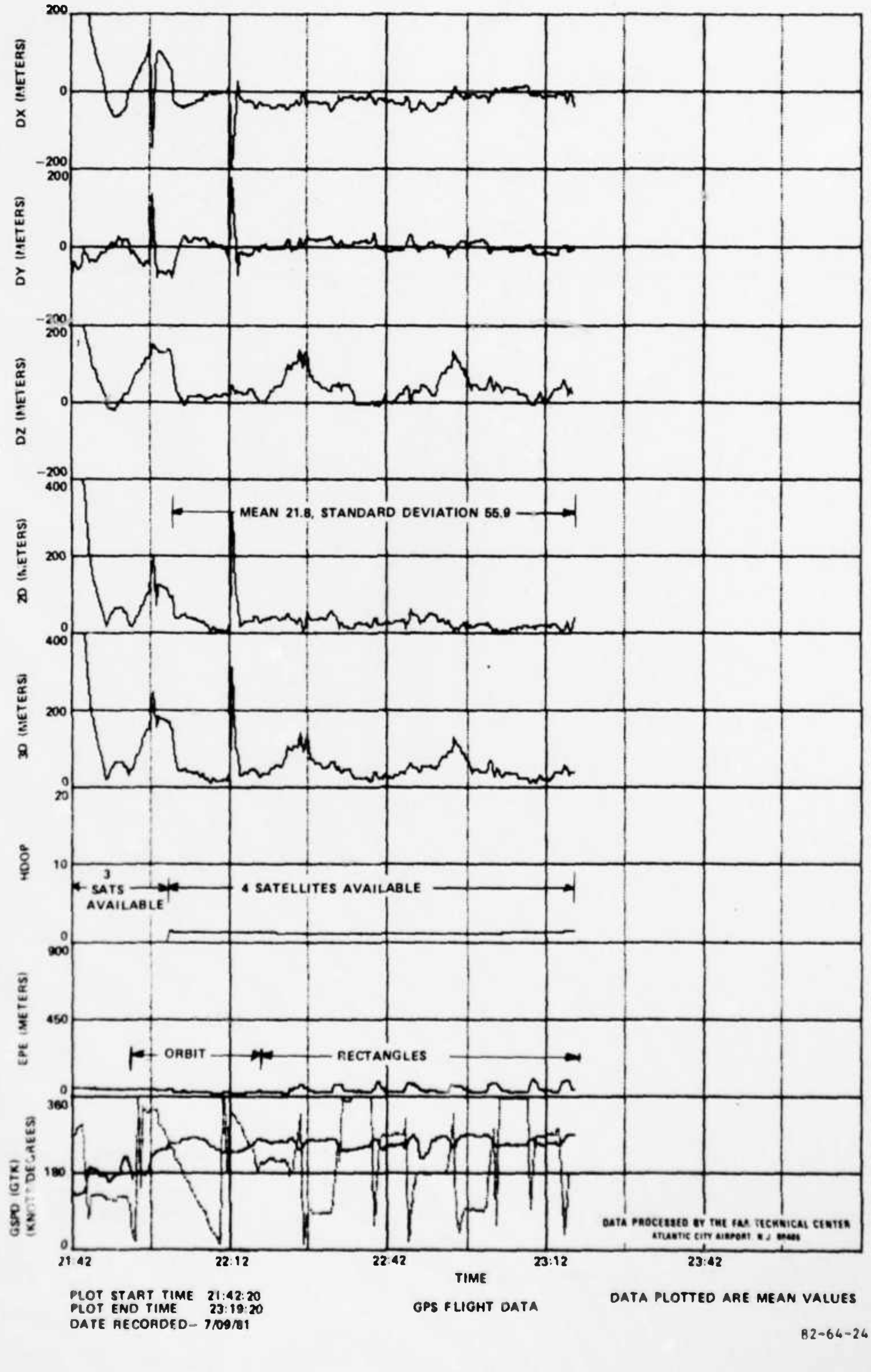
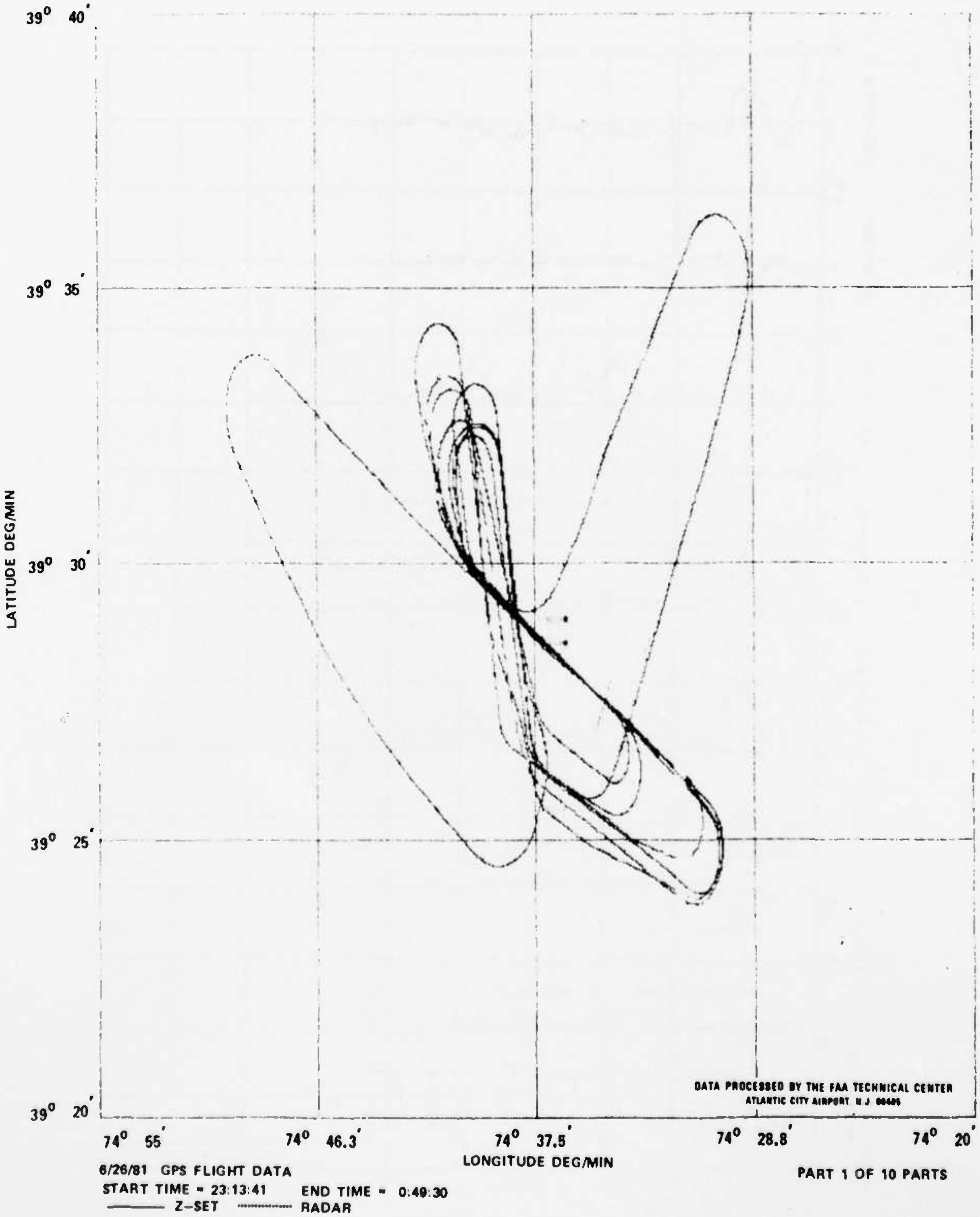
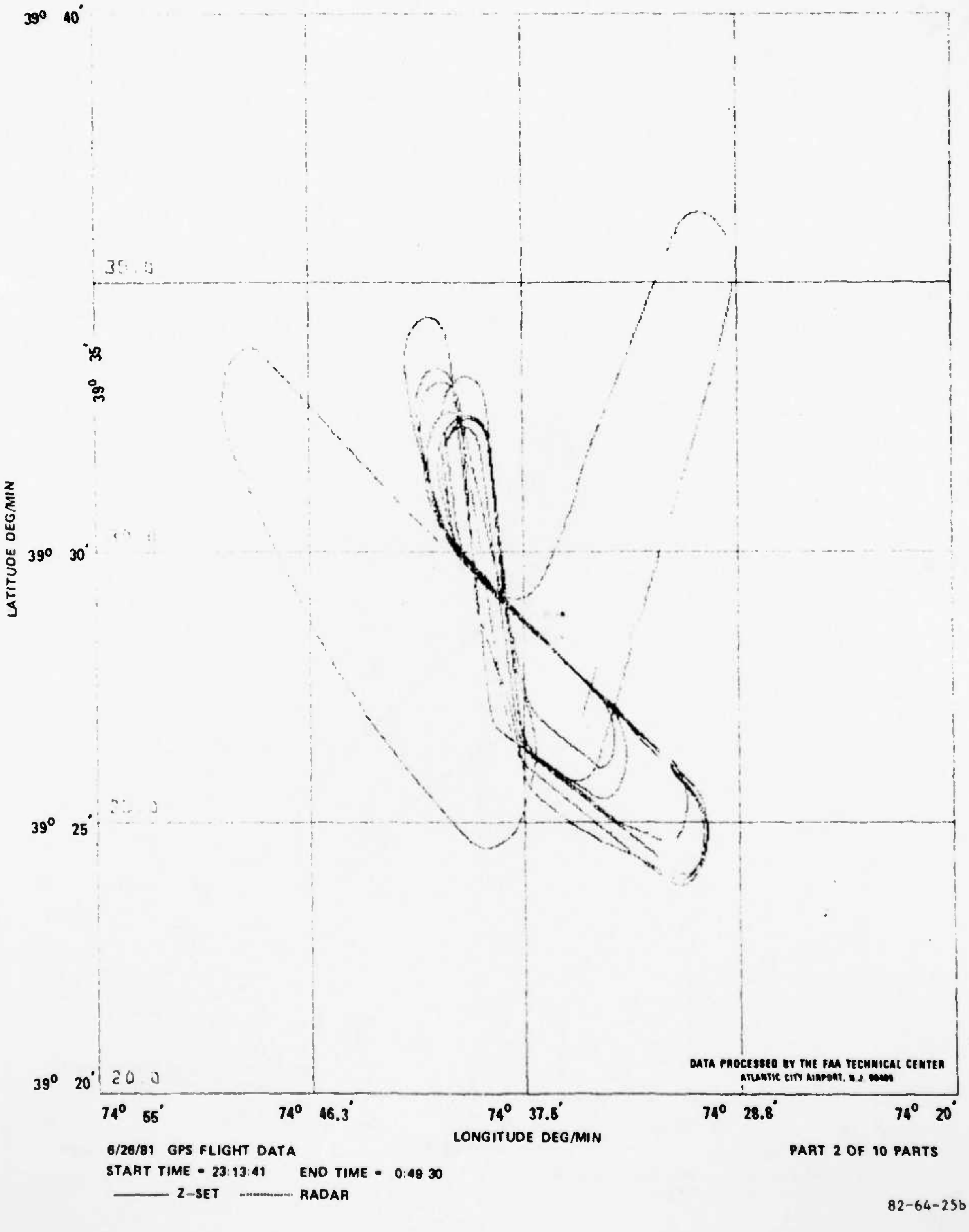


FIGURE 24. DELTA MEAN PLOT FOR JULY 9, 1981



82-64-25a

FIGURE 25. GPS AND RADAR DETERMINED NONPRECISION FLIGHTPATH ON JUNE 26, 1981 (SHEET 1 OF 10)



82-64-25b

FIGURE 25. GPS AND RADAR DETERMINED NONPRECISION FLIGHTPATH ON JUNE 26, 1981 (SHEET 2 OF 10)

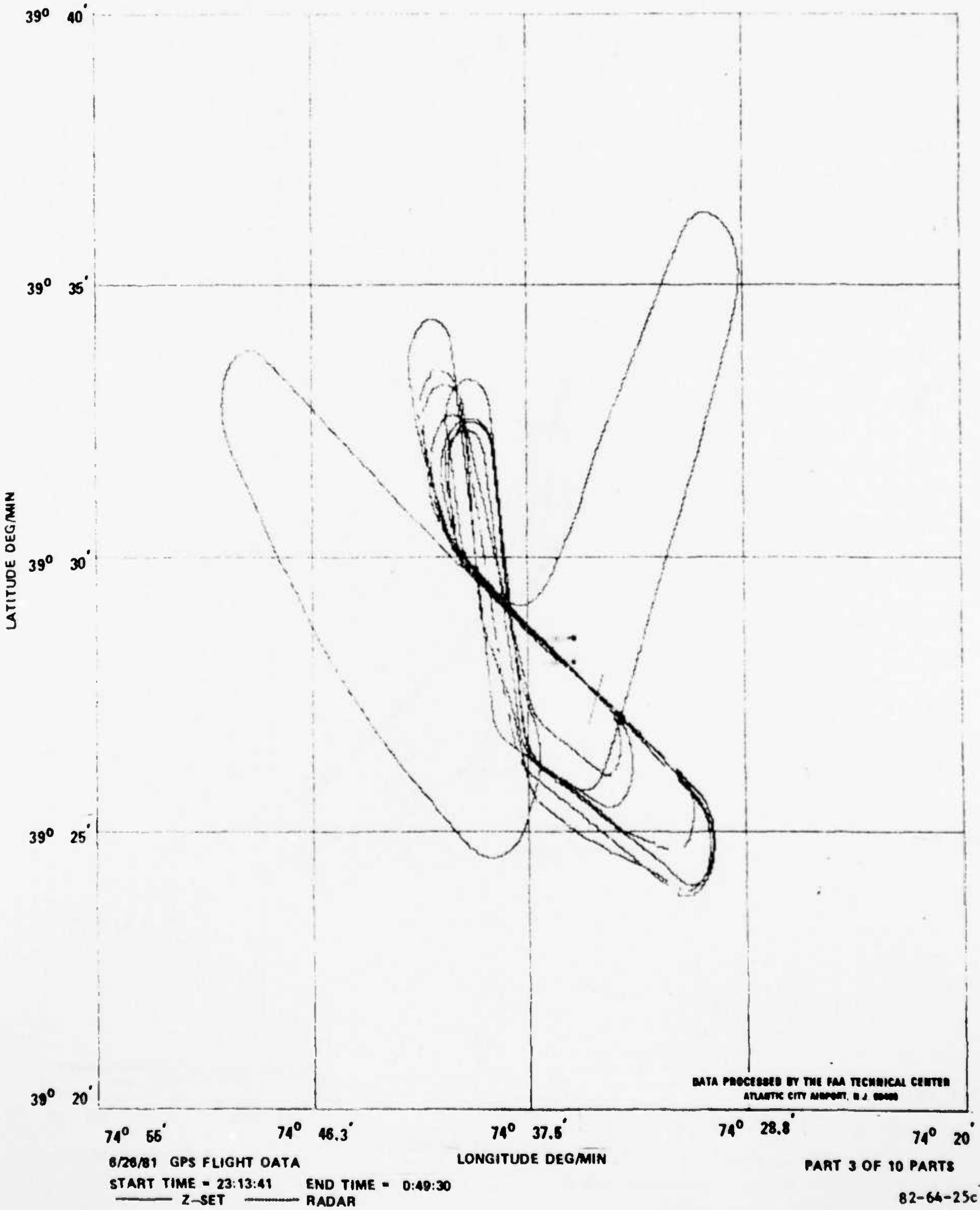
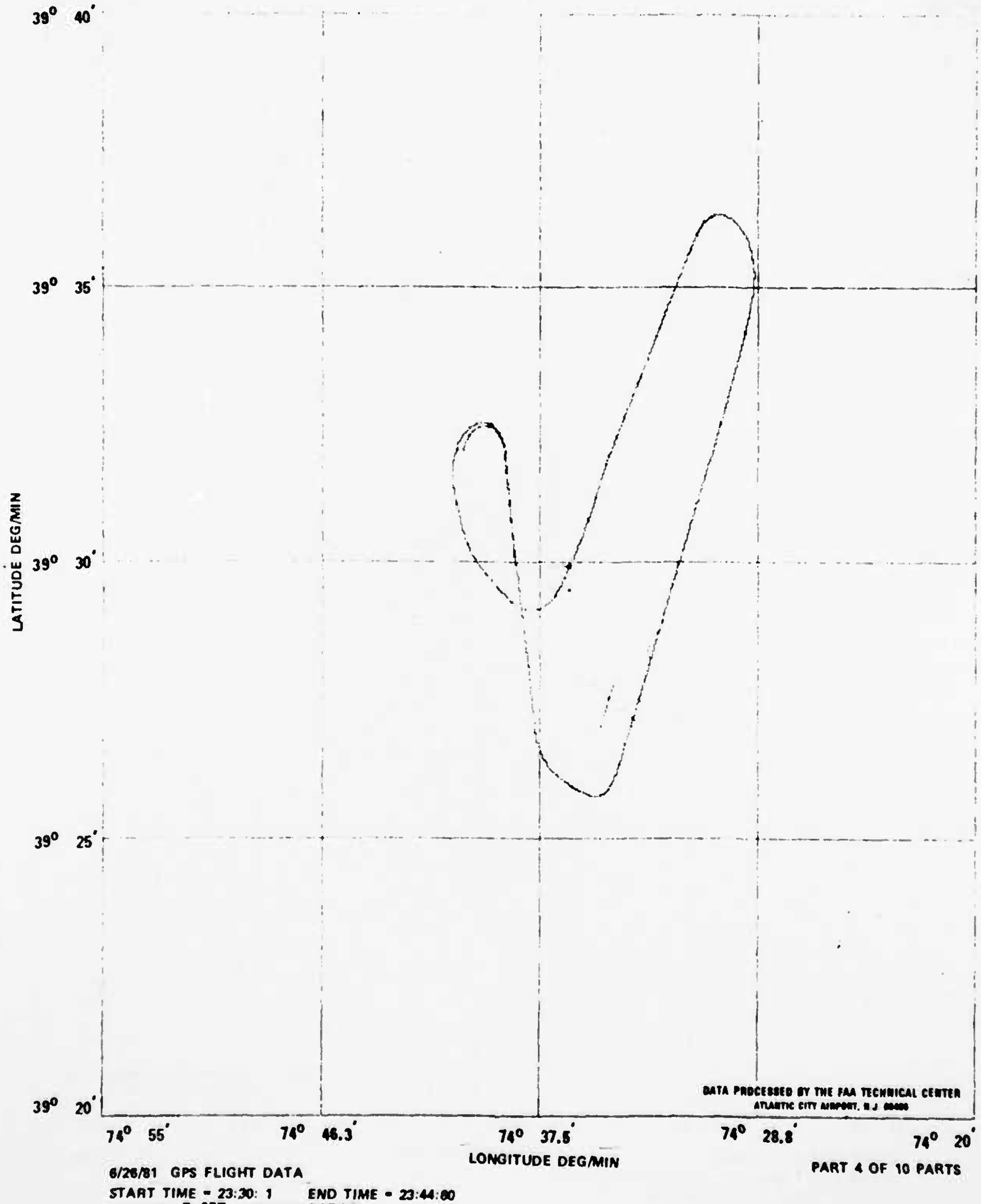


FIGURE 25. GPS AND RADAR DETERMINED NONPRECISION FLIGHTPATH ON JUNE 26, 1981 (SHEET 3 OF 10)



82-64-25d

FIGURE 25. GPS AND RADAR DETERMINED NONPRECISION FLIGHTPATH ON JUNE 26, 1981 (SHEET 4 OF 10)

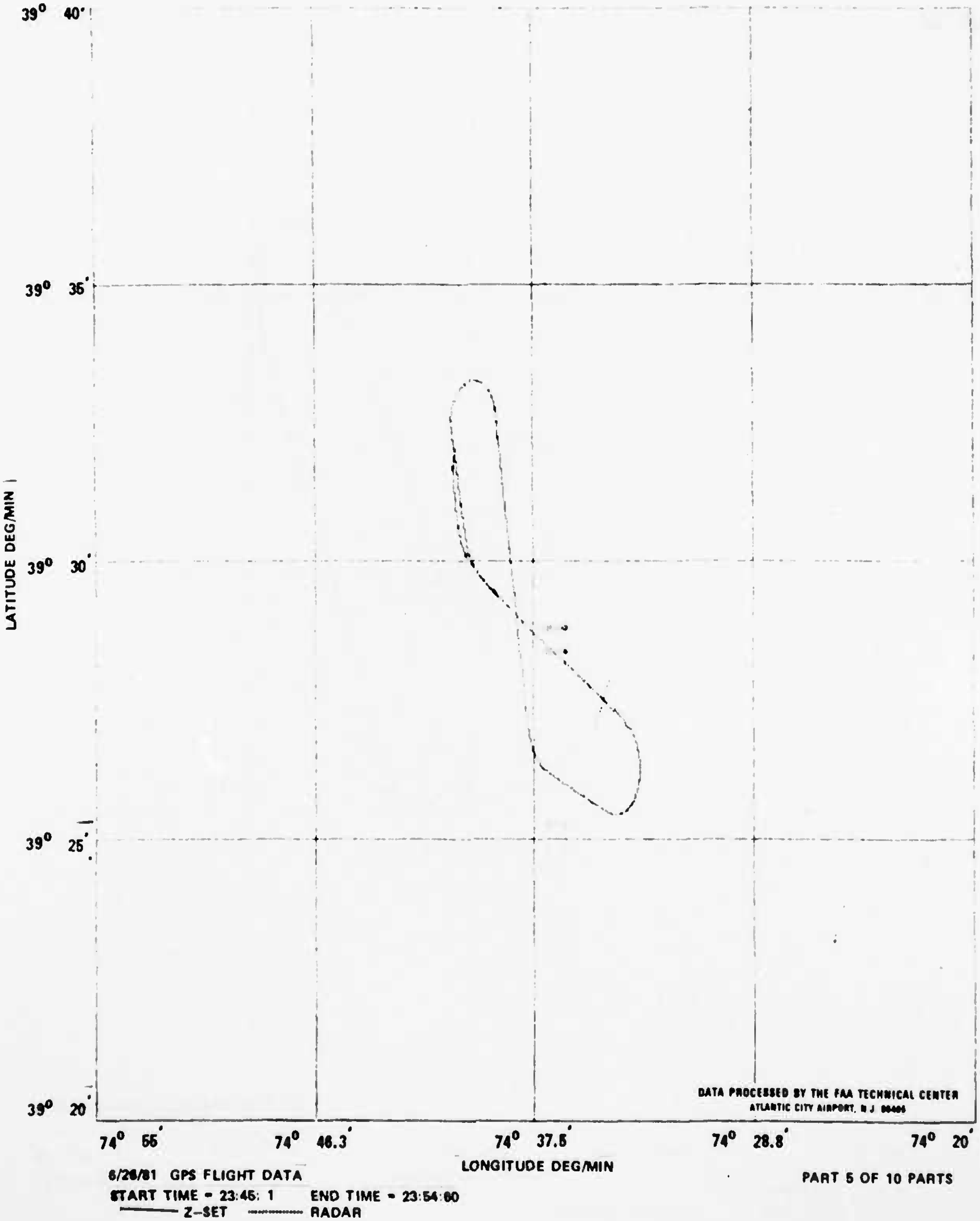


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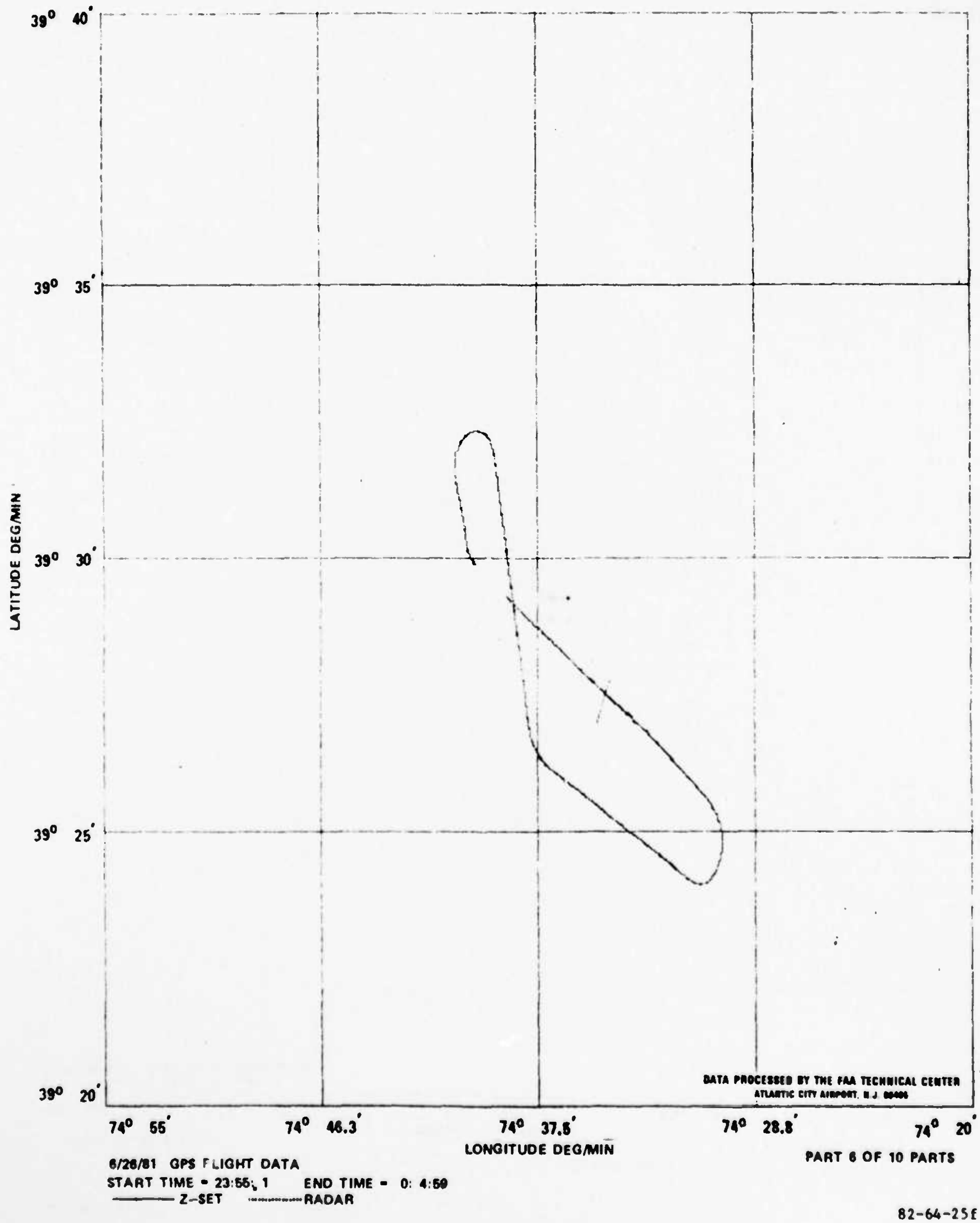
FIGURE 25. GPS AND RADAR DETERMINED NONPRECISION FLIGHTPATH ON JUNE 26, 1981 (SHEET 5 OF 10)



82-64-25f

FIGURE 25. GPS AND RADAR DETERMINED NONPRECISION FLIGHTPATH ON JUNE 26, 1981 (SHEET 6 OF 10)

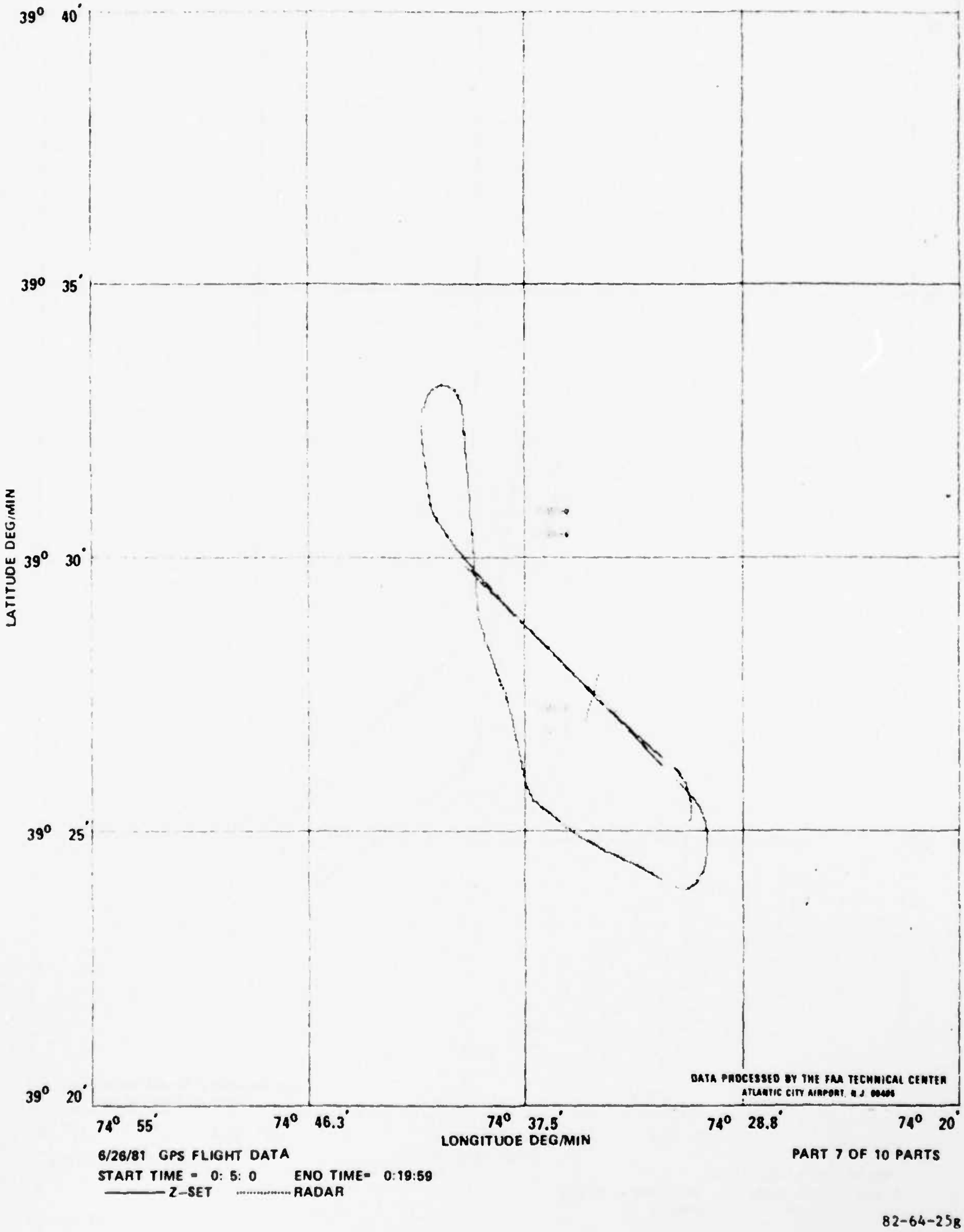


FIGURE 25. GPS AND RADAR DETERMINED NONPRECISION FLIGHTPATH ON JUNE 26, 1981 (SHEET 7 OF 10)

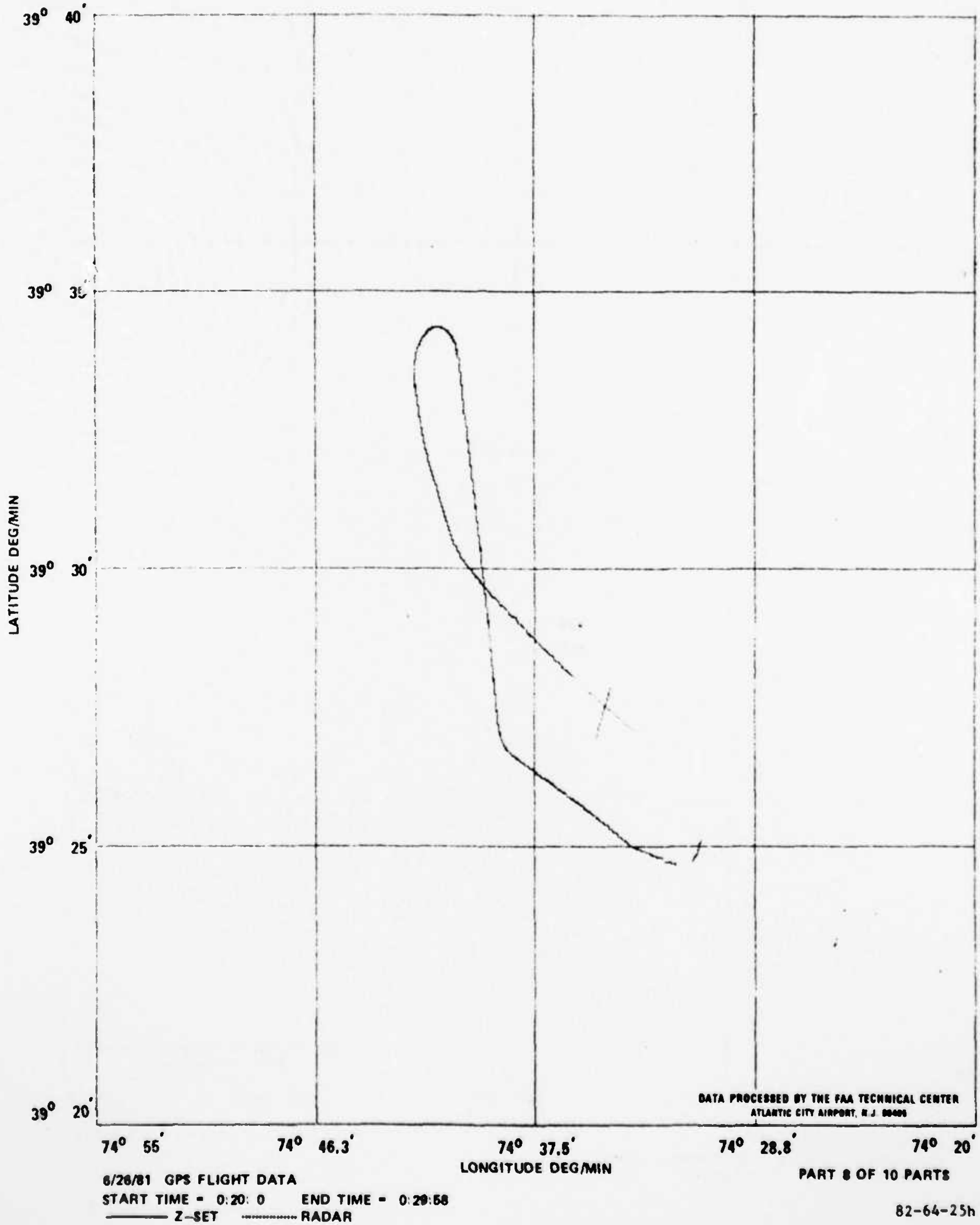
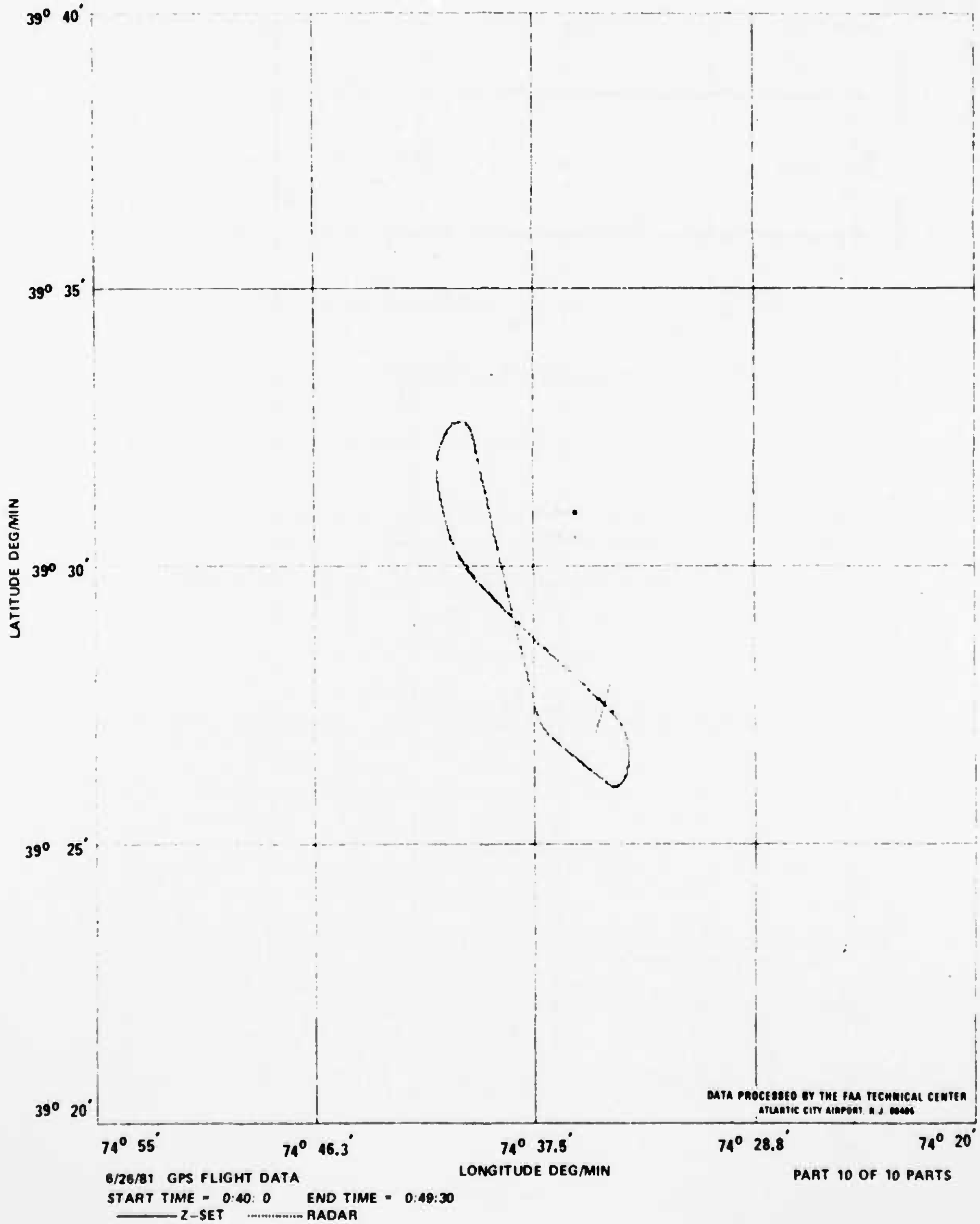


FIGURE 25. GPS AND RADAR DETERMINED NONPRECISION FLIGHTPATH ON JUNE 26, 1981 (SHEET 8 OF 10)

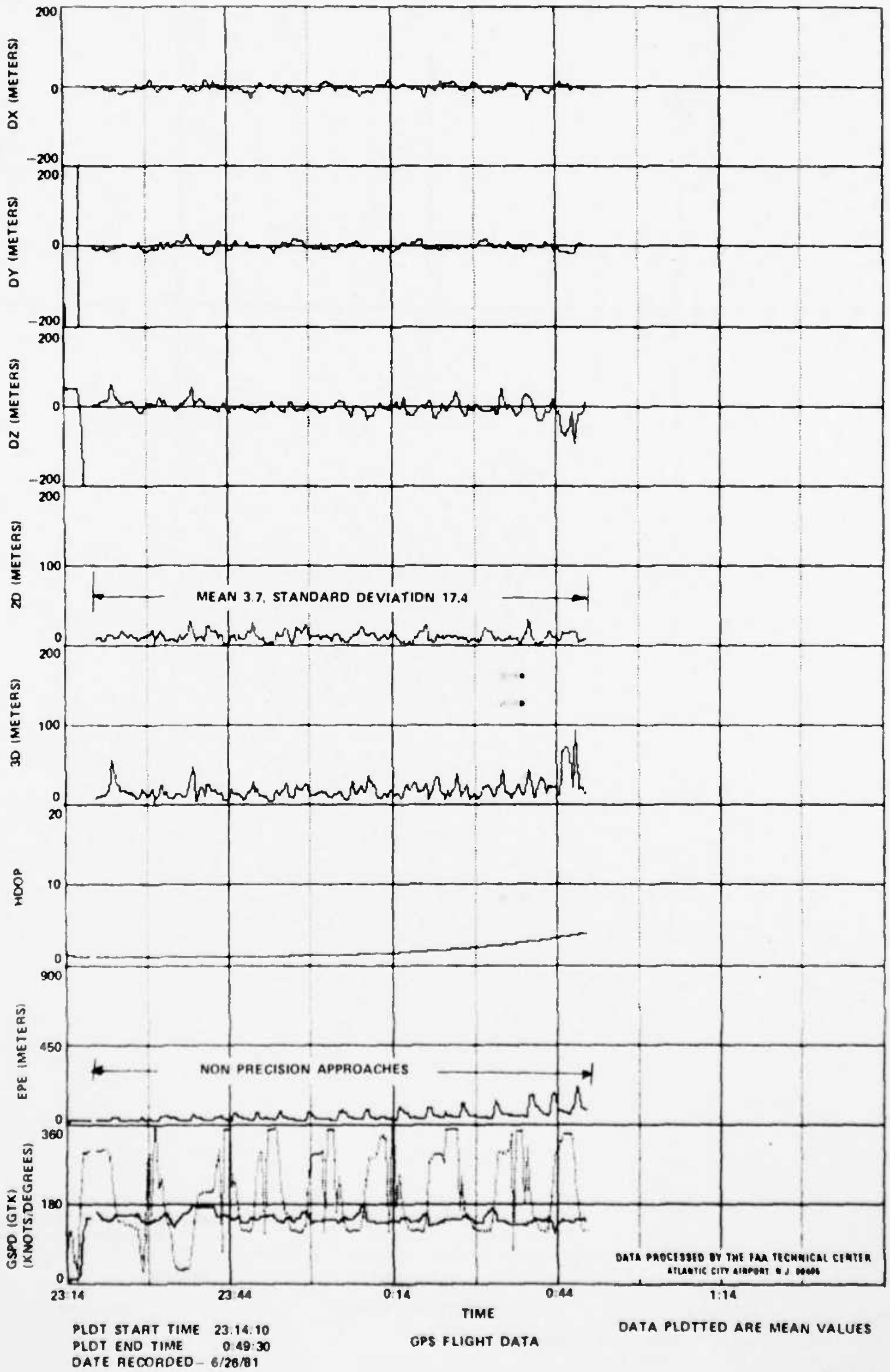
82-64-25i

FIGURE 25. GPS AND RADAR DETERMINED NONPRECISION FLIGHTPATH ON JUNE 26, 1981 (SHEET 9 OF 10)



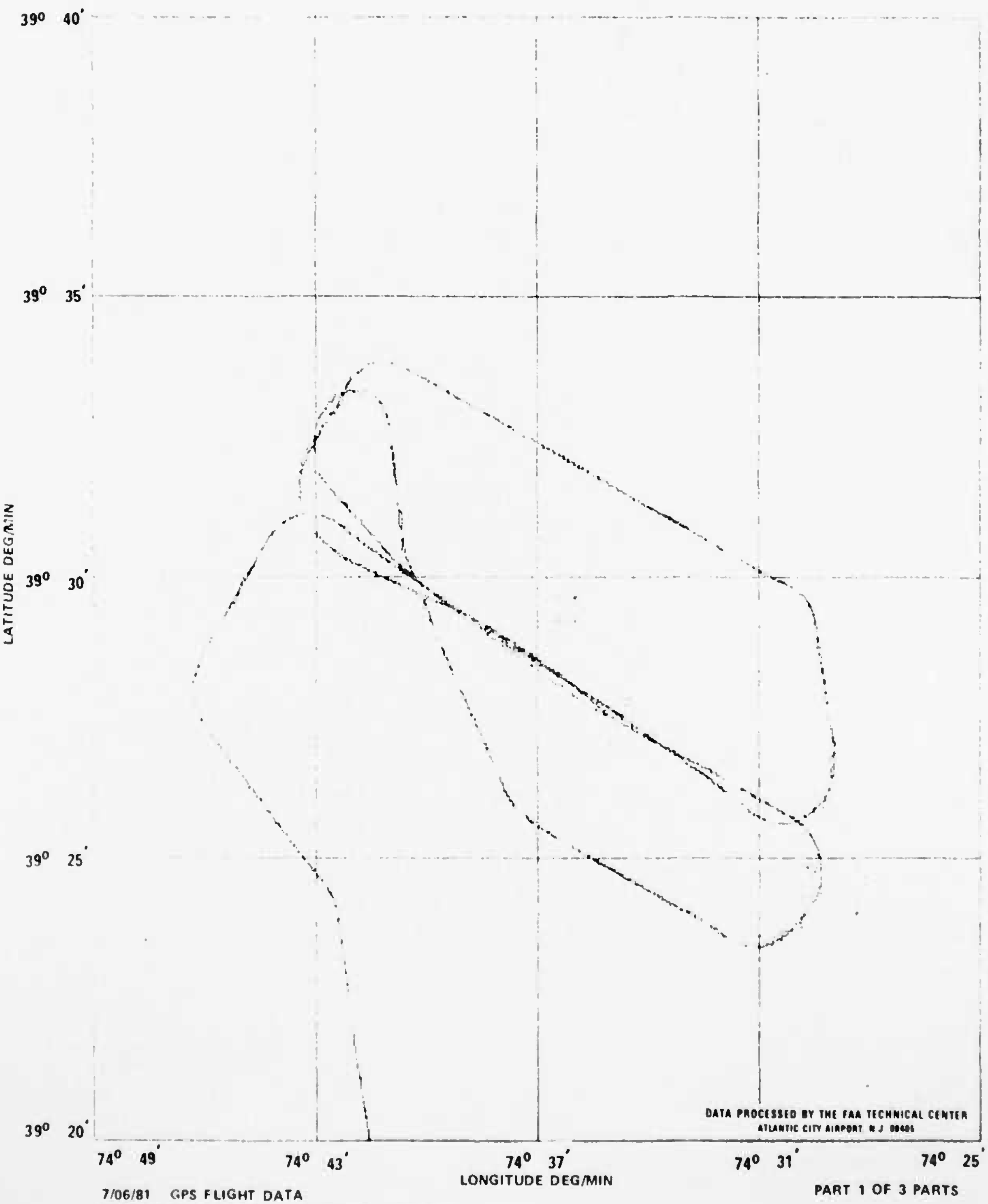
82-64-25j

FIGURE 25. GPS AND RADAR DETERMINED NONPRECISION FLIGHTPATH ON JUNE 26, 1981 (SHEET 10 OF 10)



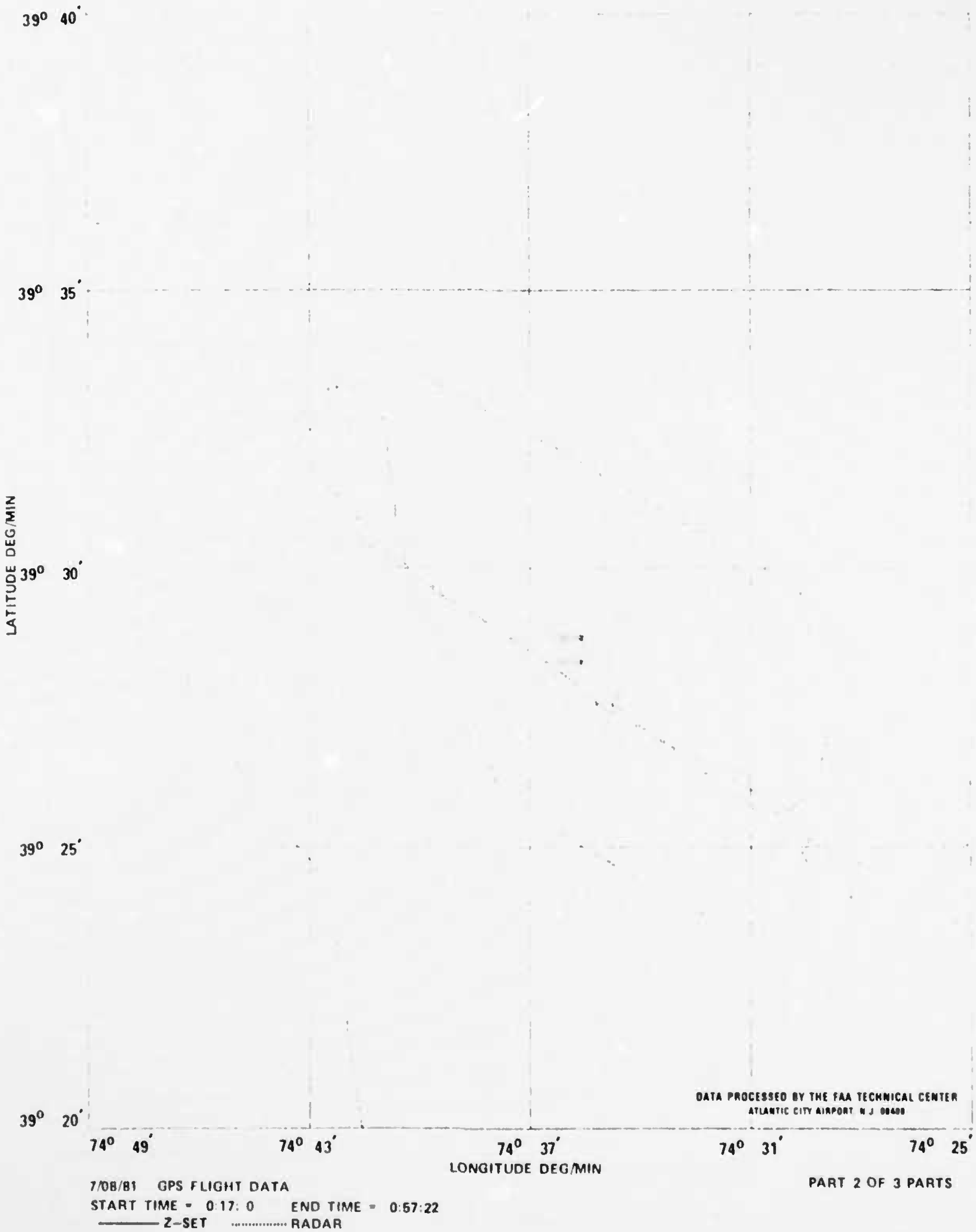
82-64-26

FIGURE 26. DELTA MEAN PLOT FOR JUNE 26, 1981



82-64-27a

FIGURE 27. GPS AND RADAR DERIVED NONPRECISION FLIGHTPATH ON JULY 6, 1981 (SHEET 1 OF 3)

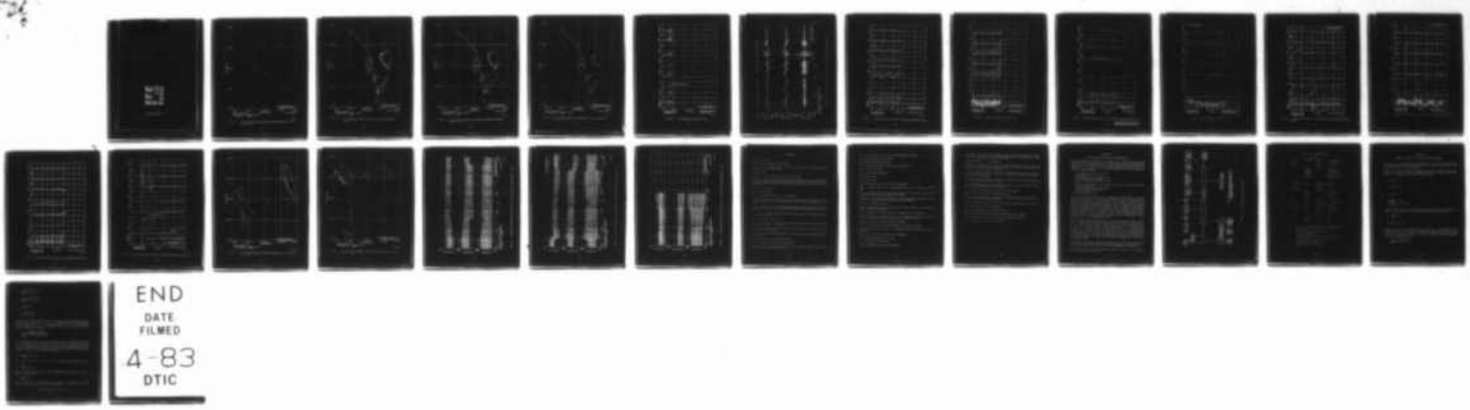


82-64-27b

FIGURE 27. GPS AND RADAR DERIVED NONPRECISION FLIGHTPATH ON JULY 6, 1981 (SHEET 2 OF 3)

AD-A125 459 GLOBAL POSITIONING SYSTEM EN ROUTE/TERMINAL EXPLORATORY TESTS(U) FEDERAL AVIATION ADMINISTRATION TECHNICAL CENTER ATLANTIC CIT.. J T CONNOR ET AL. DEC 82 2/2

UNCLASSIFIED DOT/FAA/CT-82/64 DOT/FAA/RD-82/71 F/G 17/7 NL



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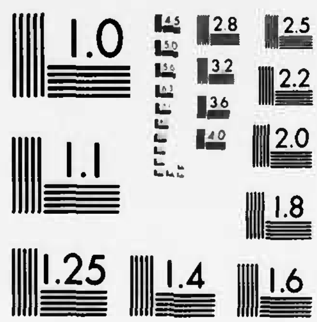
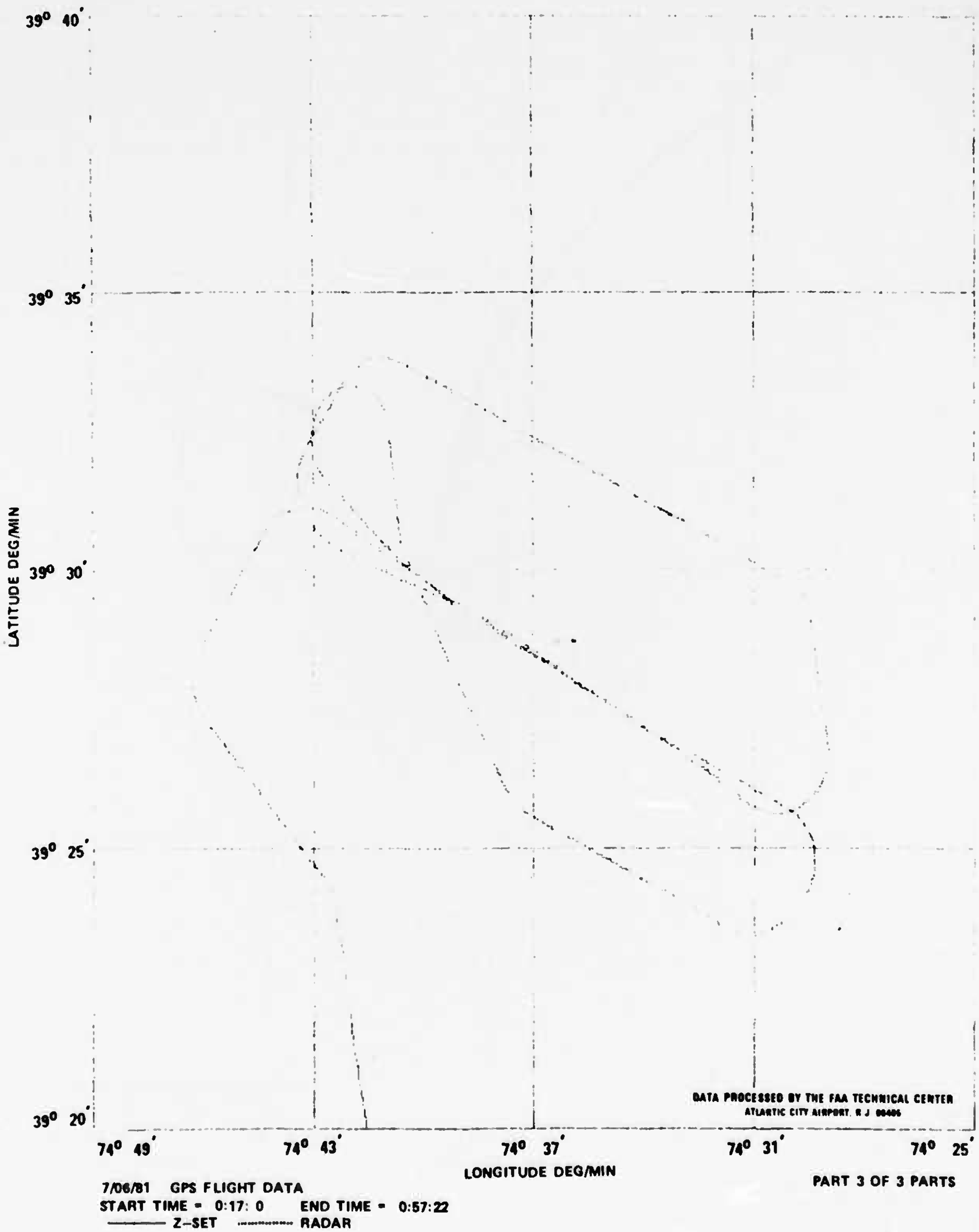


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



82-64-27c

FIGURE 27. GPS AND RADAR DERIVED NONPRECISION FLIGHTPATH ON JULY 6, 1981 (SHEET 3 OF 3)

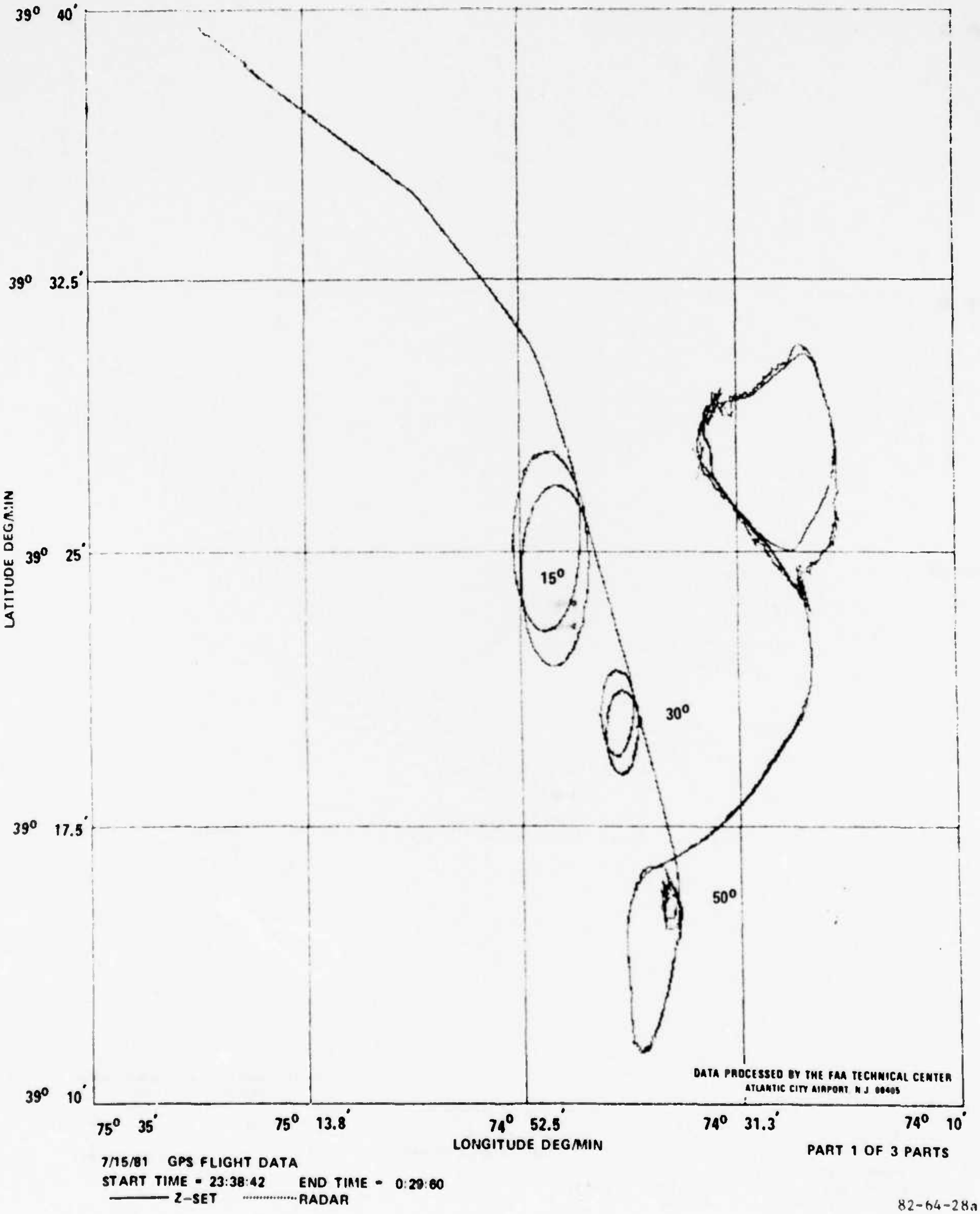
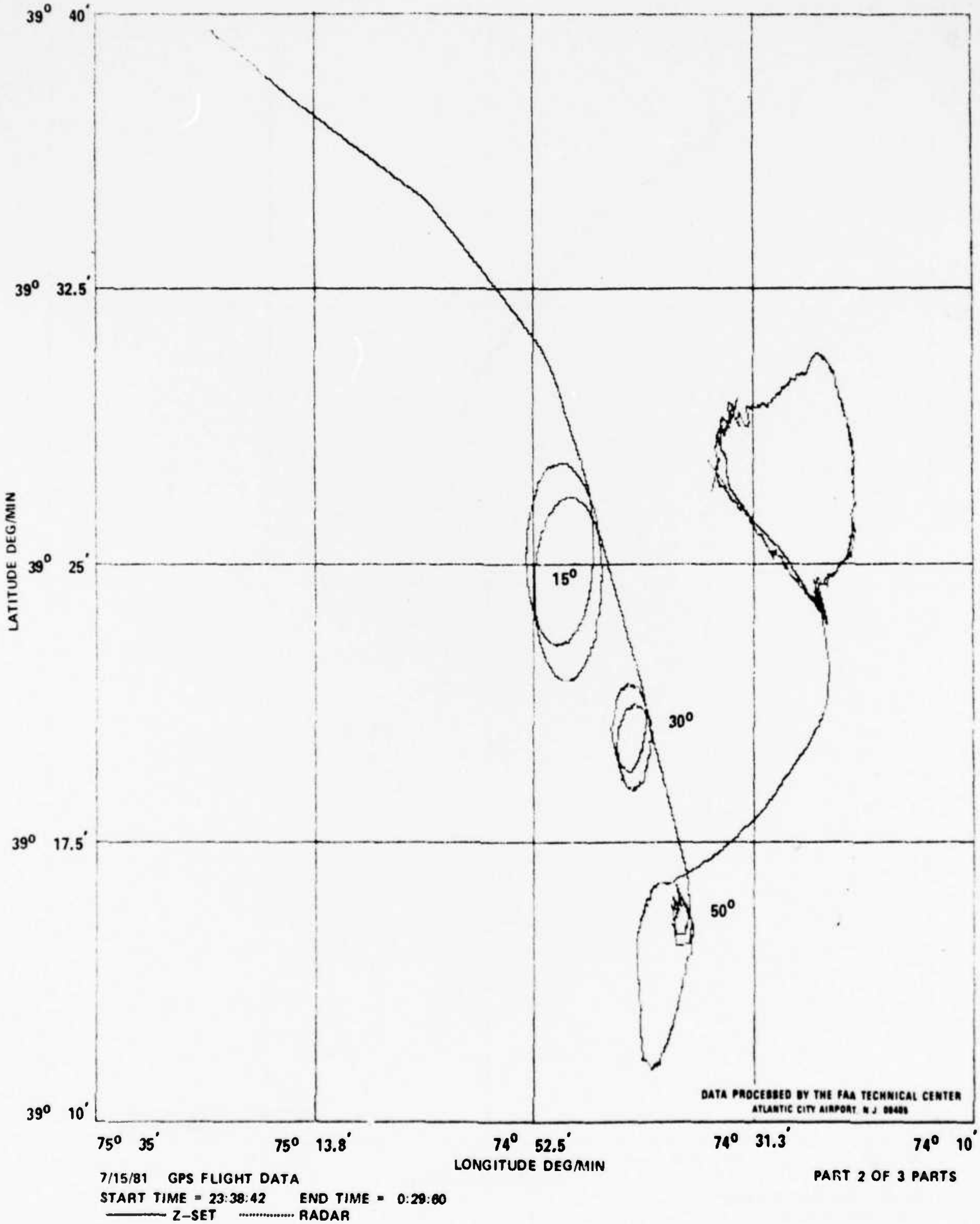


FIGURE 28. GPS AND RADAR DETERMINED FLIGHTPATH OF CONSTANT BANK TURNS (SHEET 1 OF 3)



82-64-28b

FIGURE 28. GPS AND RADAR DETERMINED FLIGHTPATH OF CONSTANT BANK TURNS (SHEET 2 OF 3)

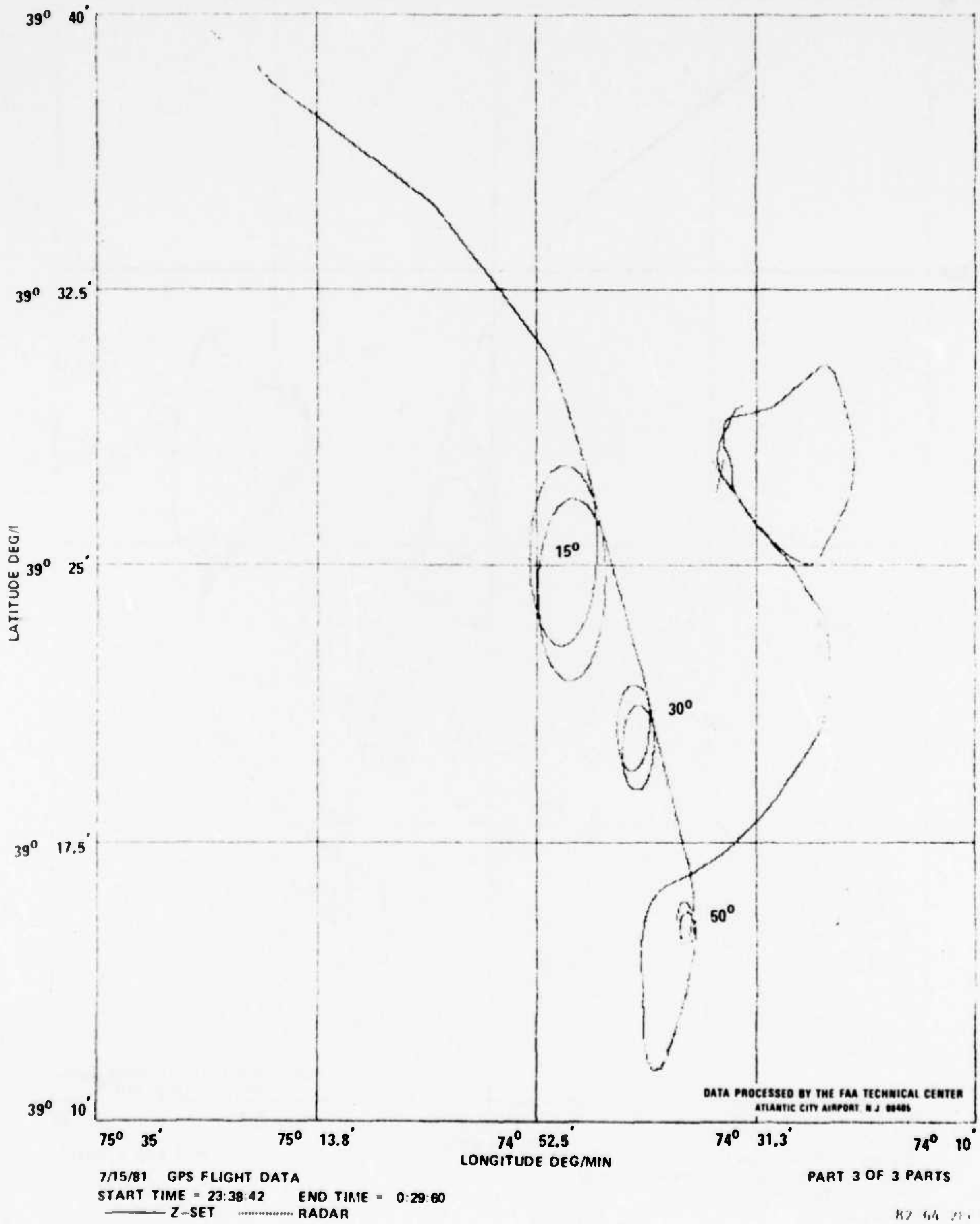


FIGURE 28. GPS AND RADAR DETERMINED FLIGHTPATH OF CONSTANT BANK TURNS (SHEET 3 OF 3)

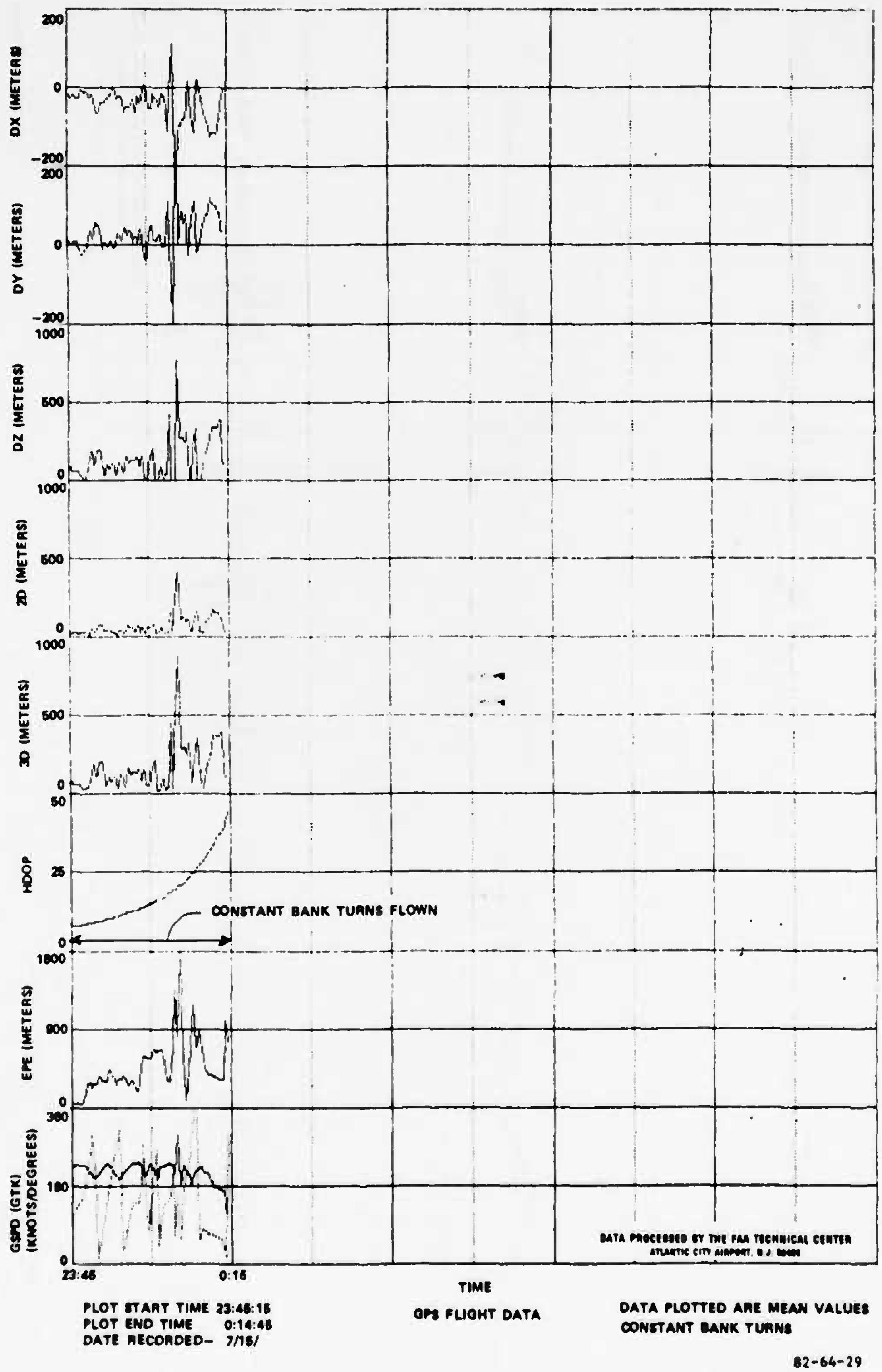


FIGURE 29. DELTA MEAN PLOT FOR JULY 15, 1981

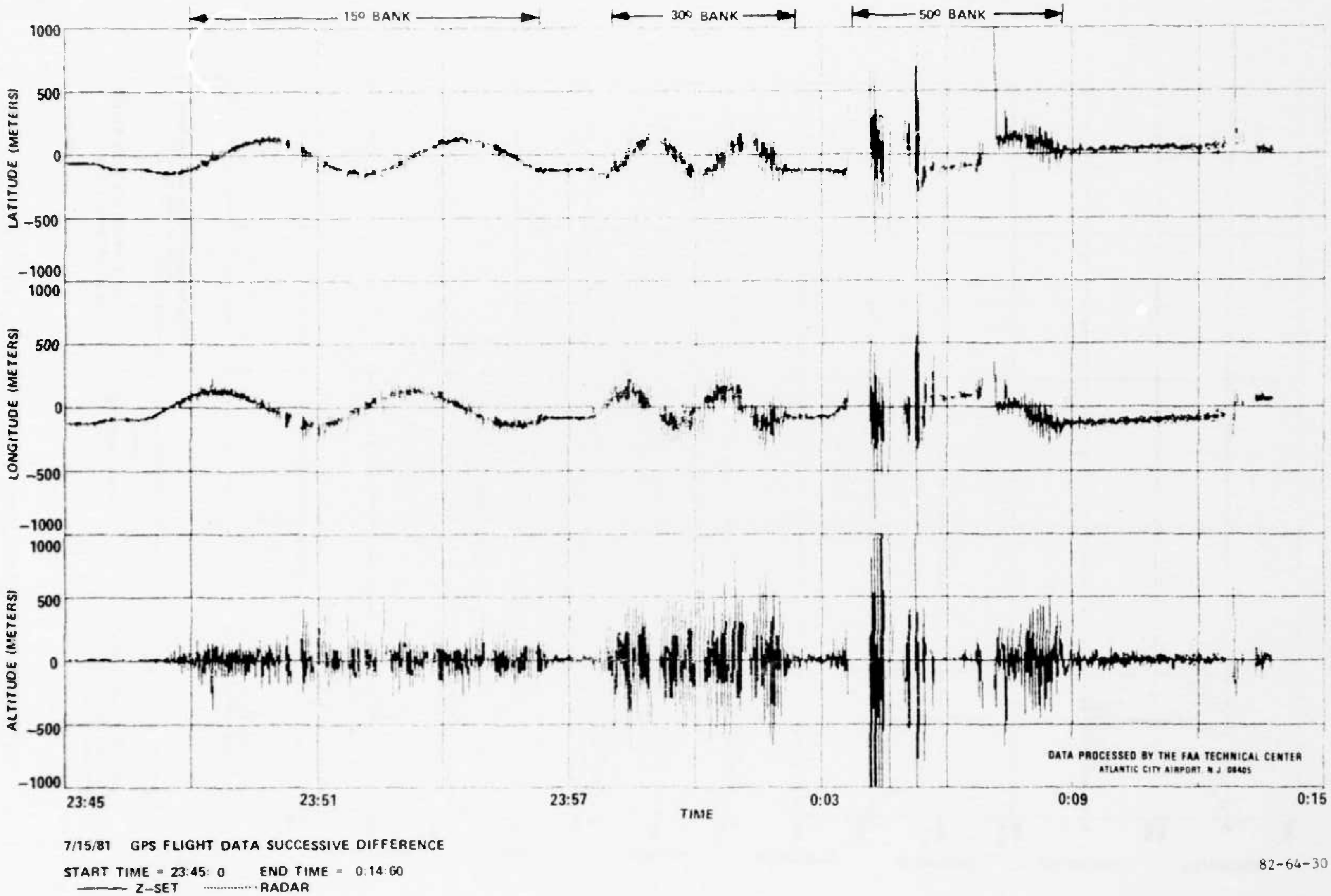


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FIGURE 30. SUCCESSIVE DIFFERENCE PLOT FOR JULY 15, 1981, FOR CONSTANT BANK TURNS

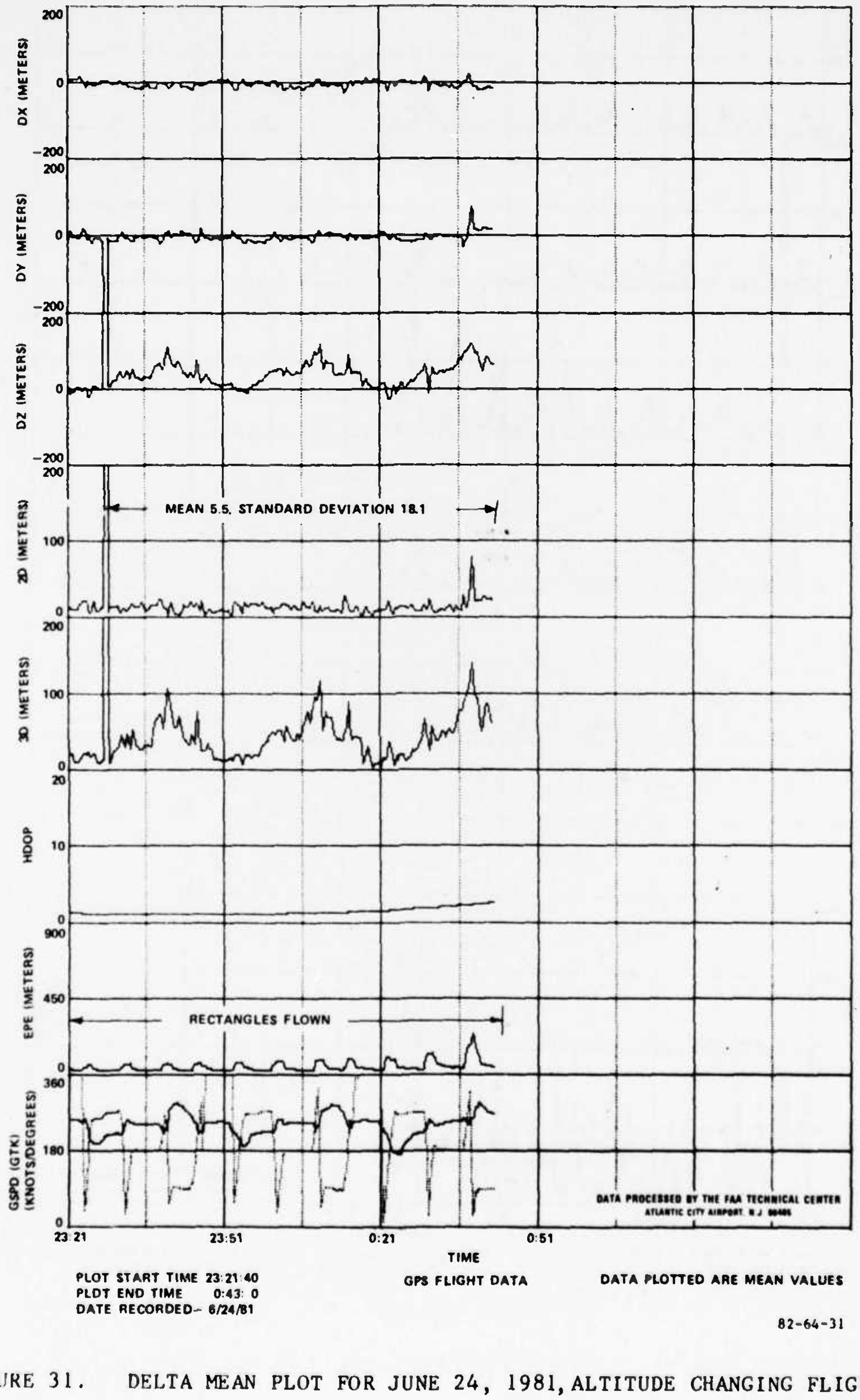

FIGURE 31. DELTA MEAN PLOT FOR JUNE 24, 1981, ALTITUDE CHANGING FLIGHT

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FIGURE 32. DELTA SIGMA PLOT FOR JUNE 24, 1981

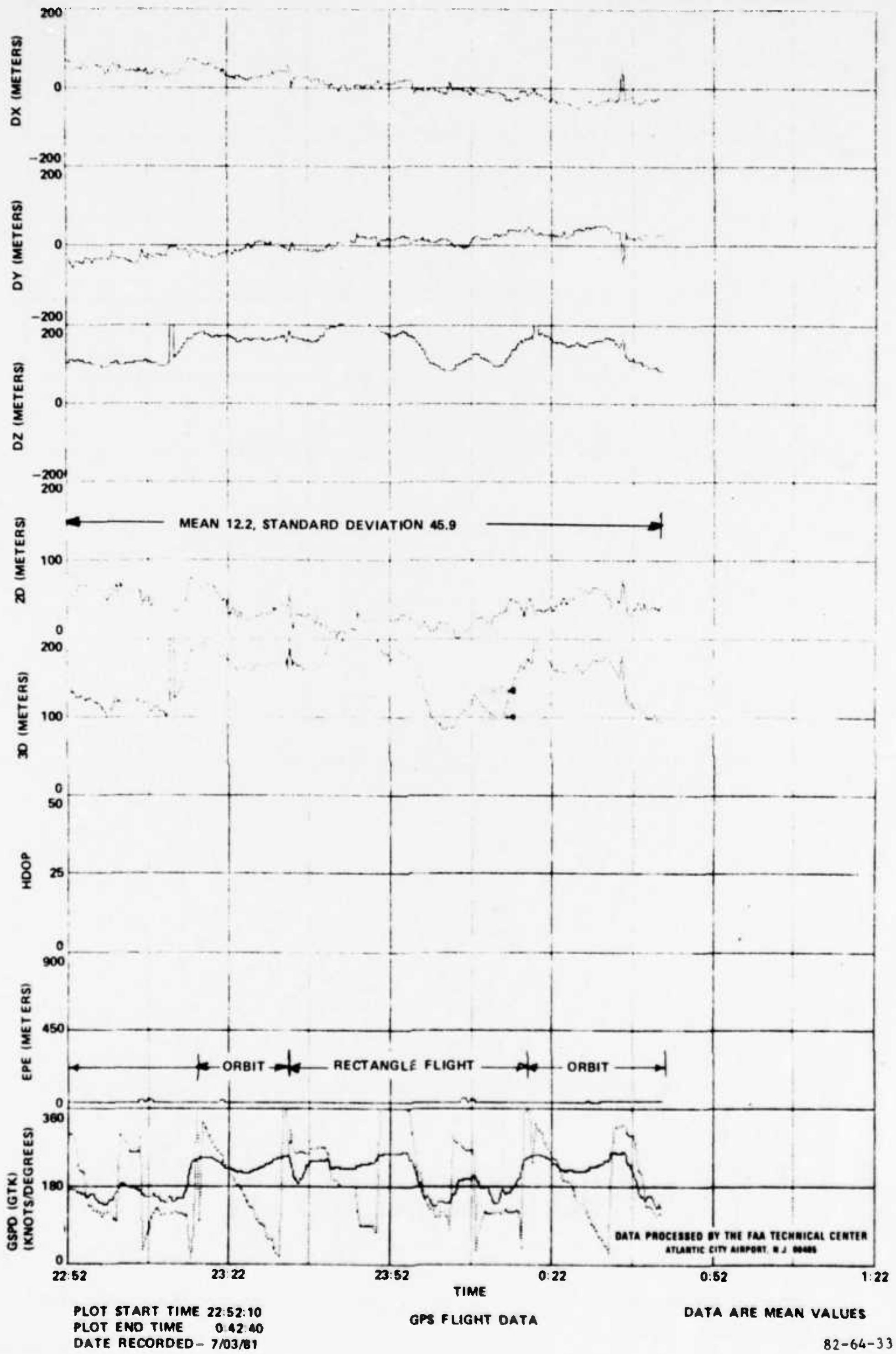

FIGURE 33. DELTA MEAN PLOT FOR JULY 3, 1981, FLIGHT USING THREE SATELLITES

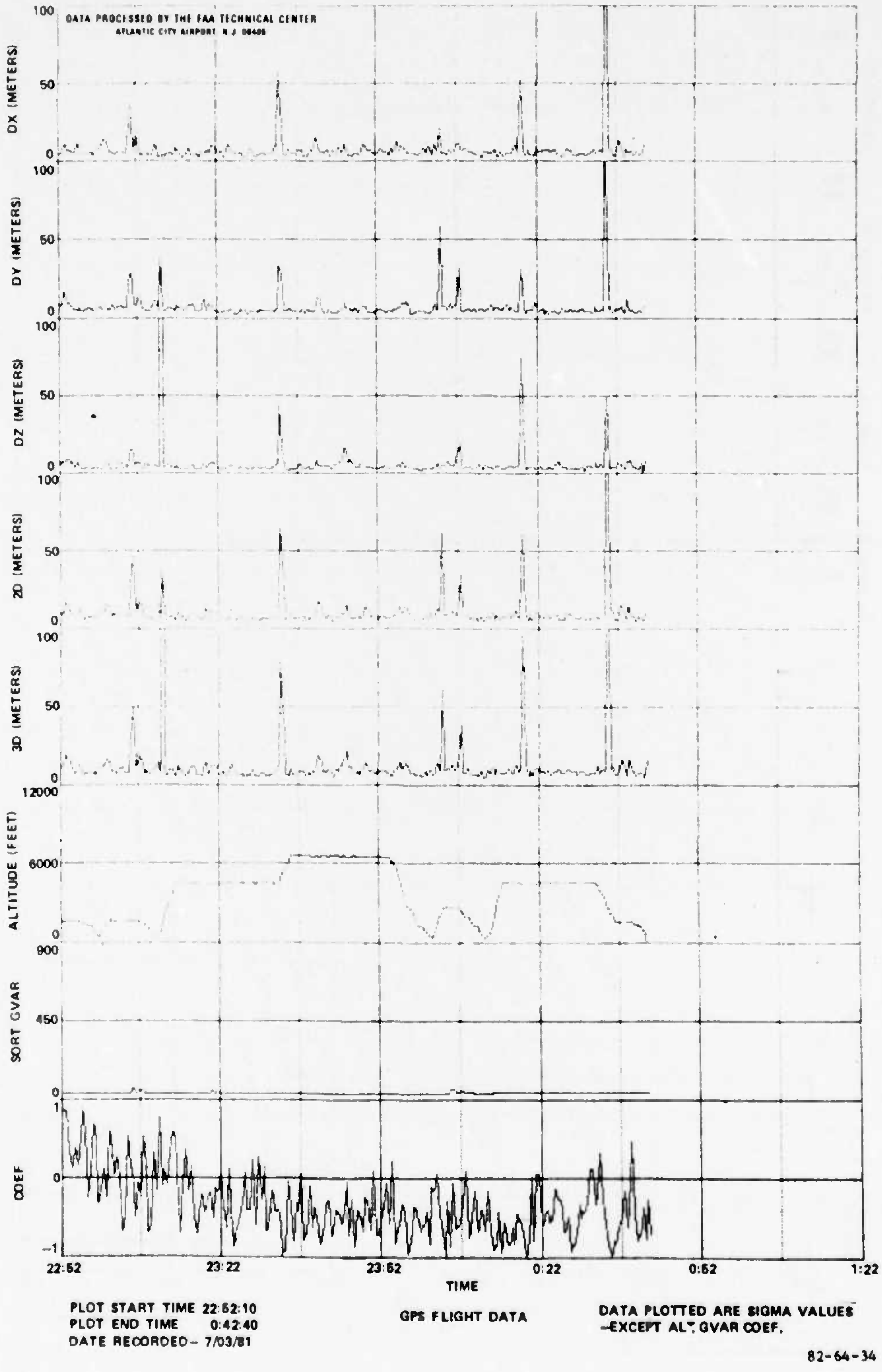

FIGURE 34. DELTA SIGMA PLOT FOR JULY 3, 1981

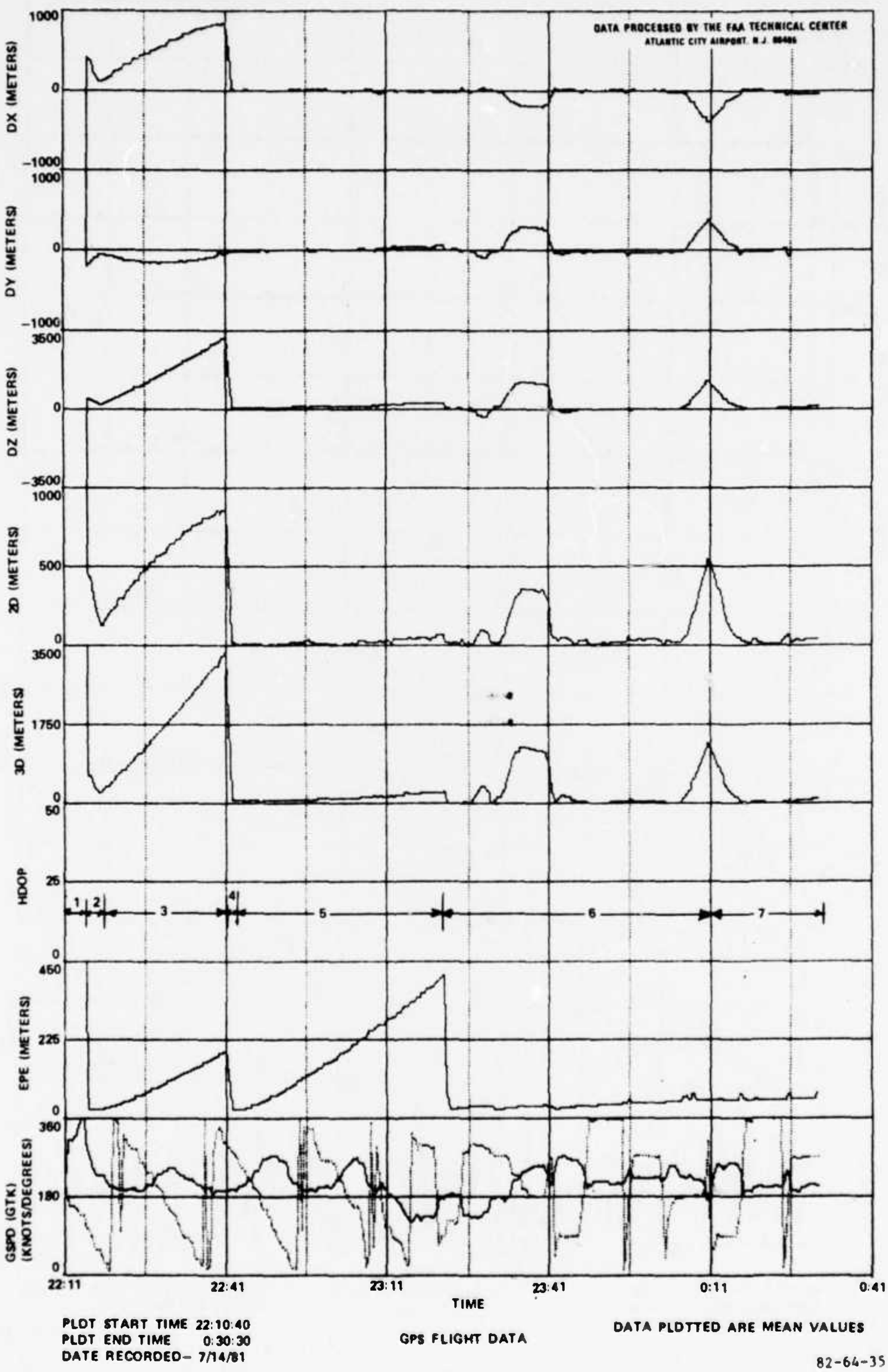

FIGURE 35. DELTA MEAN PLOT FOR JULY 14, 1981, FLIGHT TESTING DIGITAL ALTITUDE INPUT

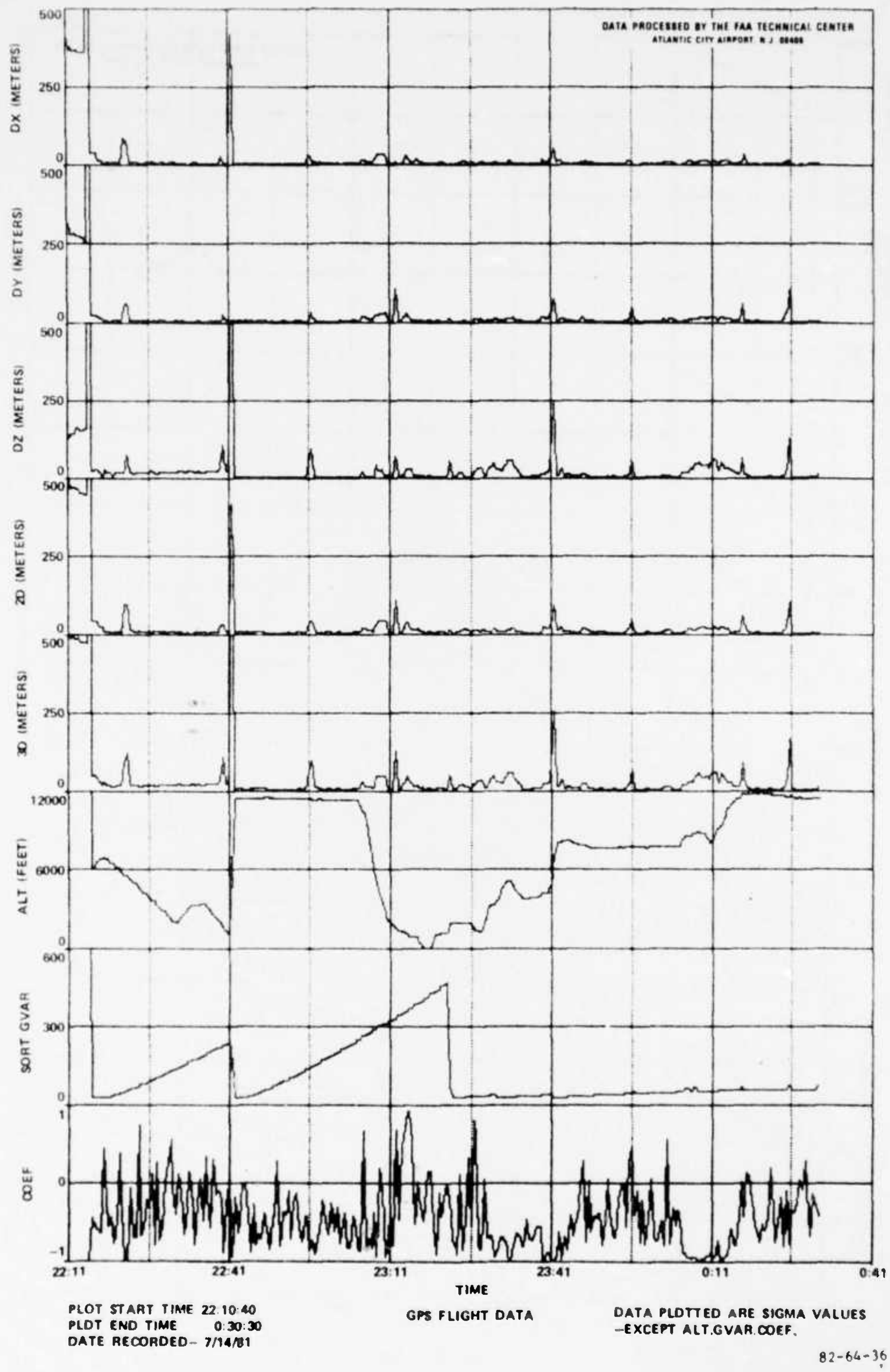

FIGURE 36. DELTA SIGMA PLOT FOR JULY 14, 1981, FLIGHT TESTING DIGITAL ALTITUDE INPUT

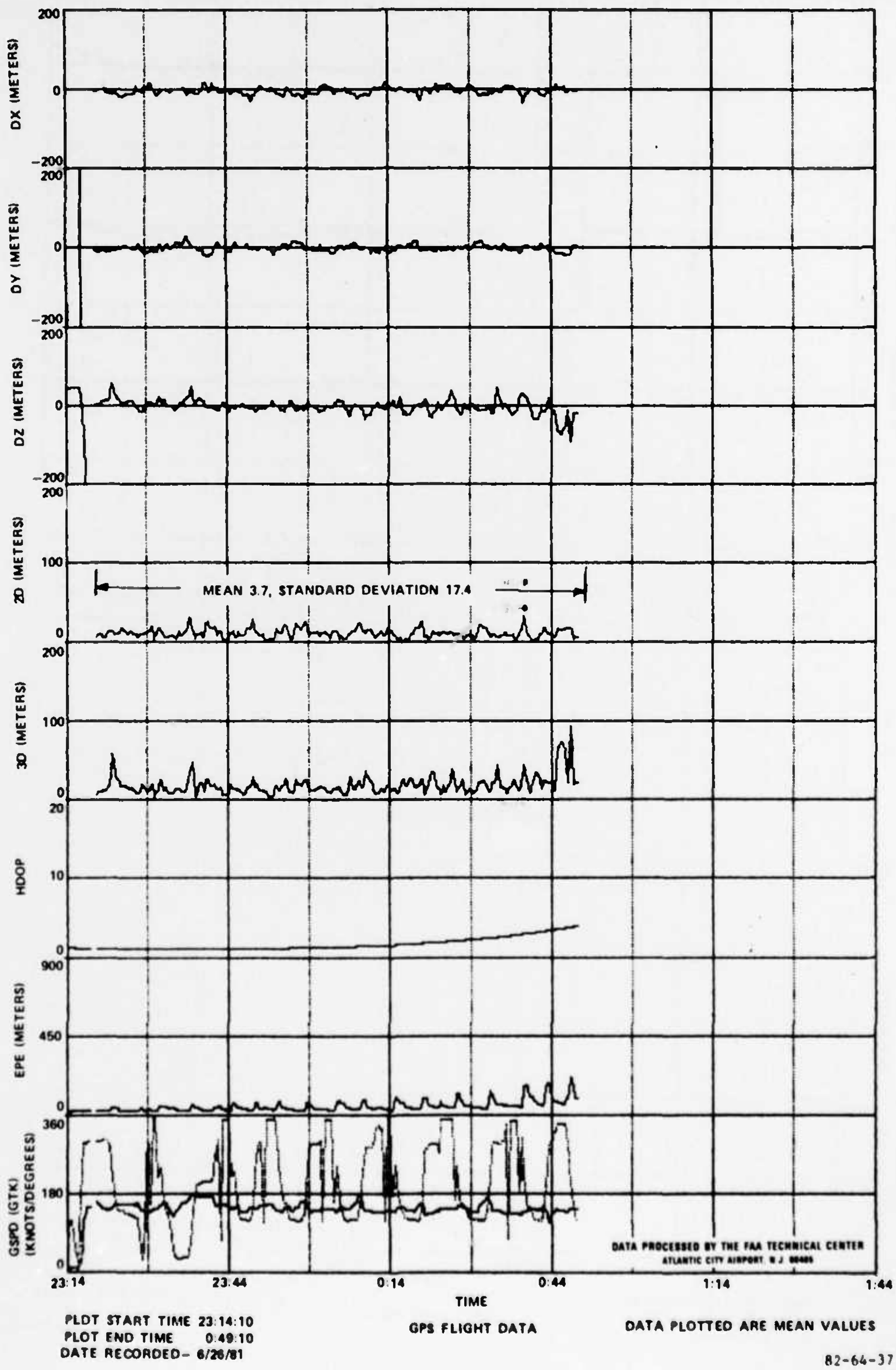

FIGURE 37. DELTA MEAN PLOT FOR JUNE 26, 1981, ANTENNA CHANGING FLIGHT

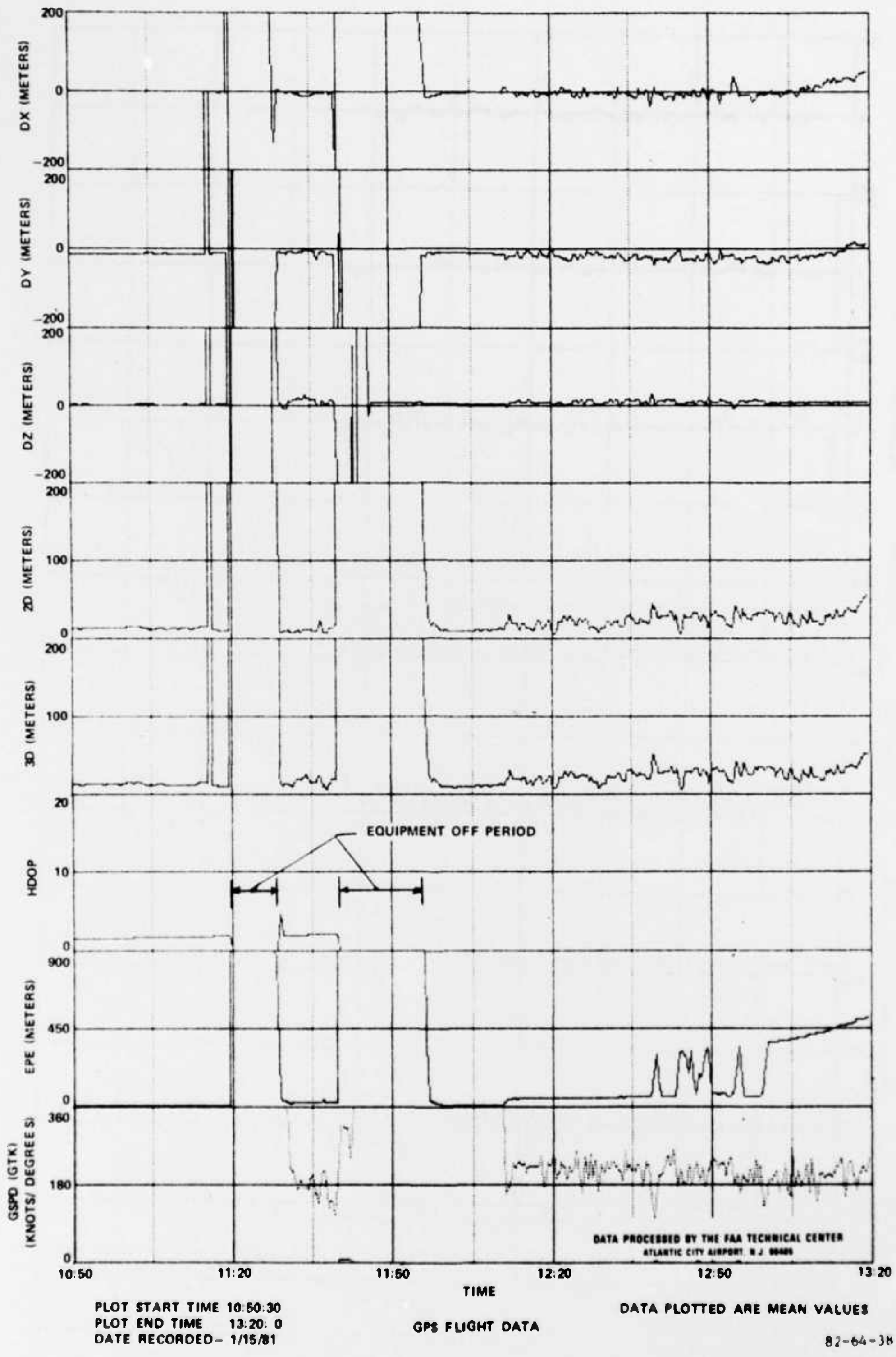

FIGURE 38. DELTA MEAN PLOT FOR JANUARY 15, 1982, DATA DURING ICING CONDITION

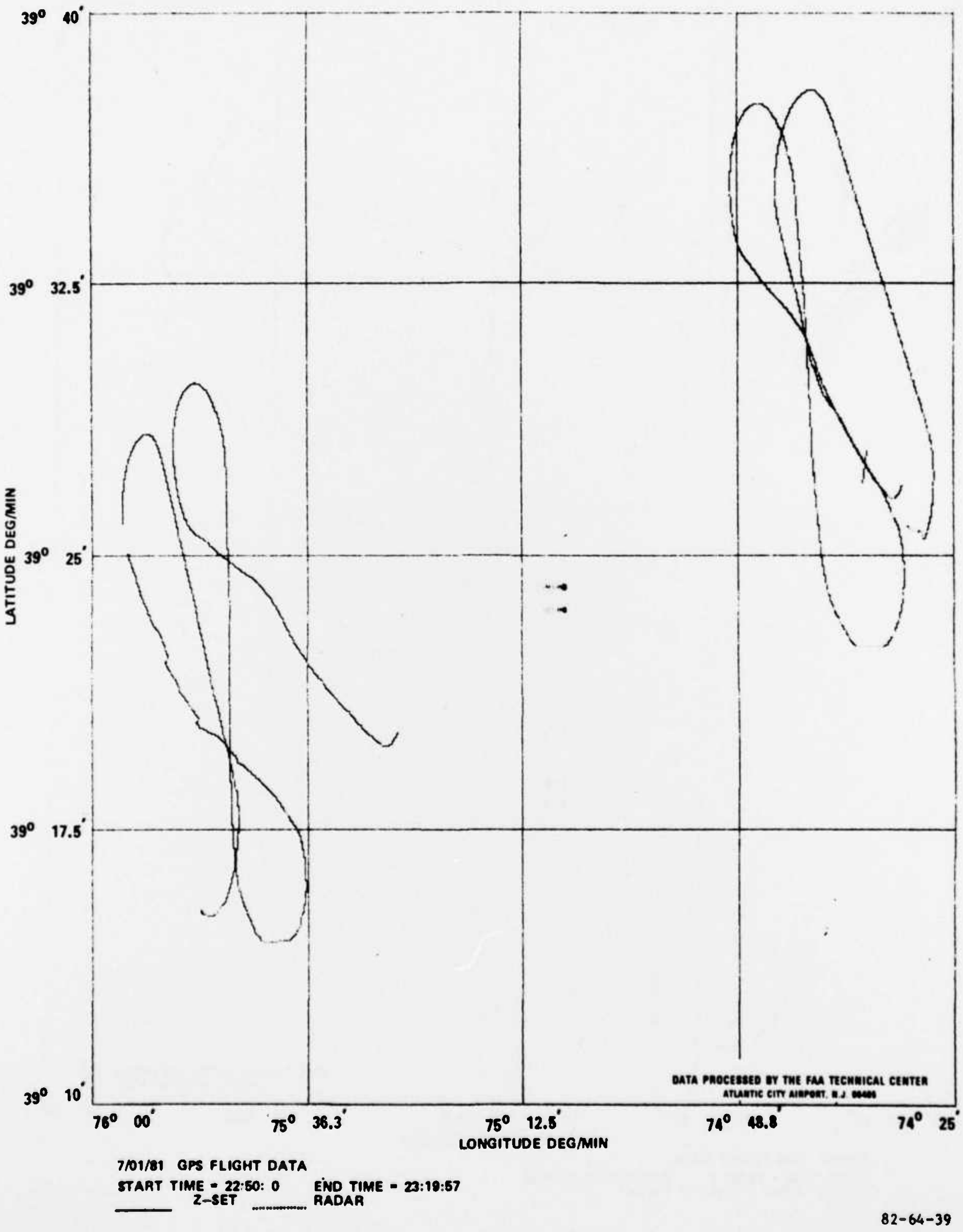

FIGURE 39. GPS AND RADAR DETERMINED FLIGHTPATH DURING Z-SET 4:3 STATUS ON JULY 1, 1981

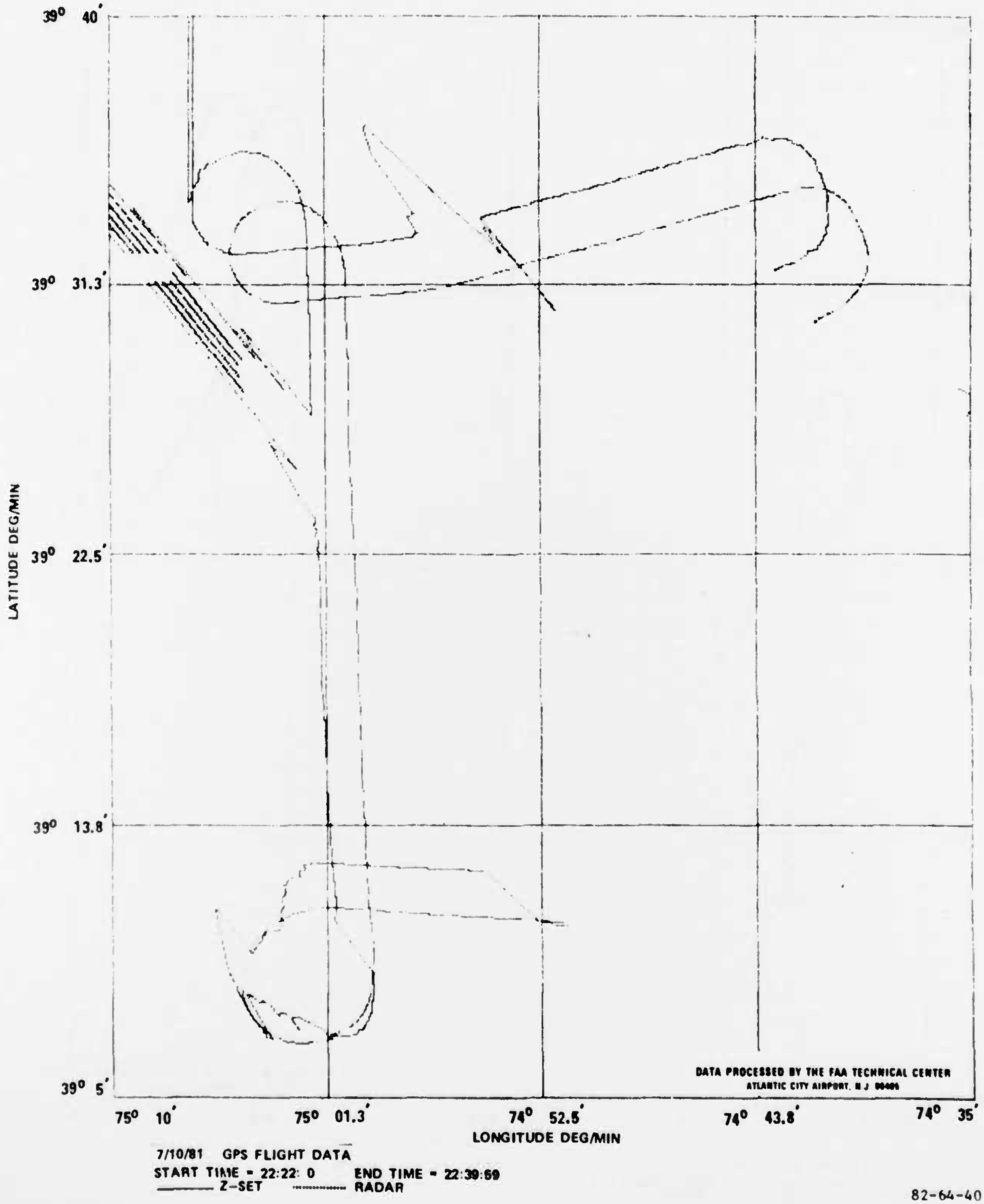

FIGURE 40. GPS AND RADAR DETERMINED FLIGHTPATH DURING Z-SET 4:3: STATUS ON JULY 10, 1981

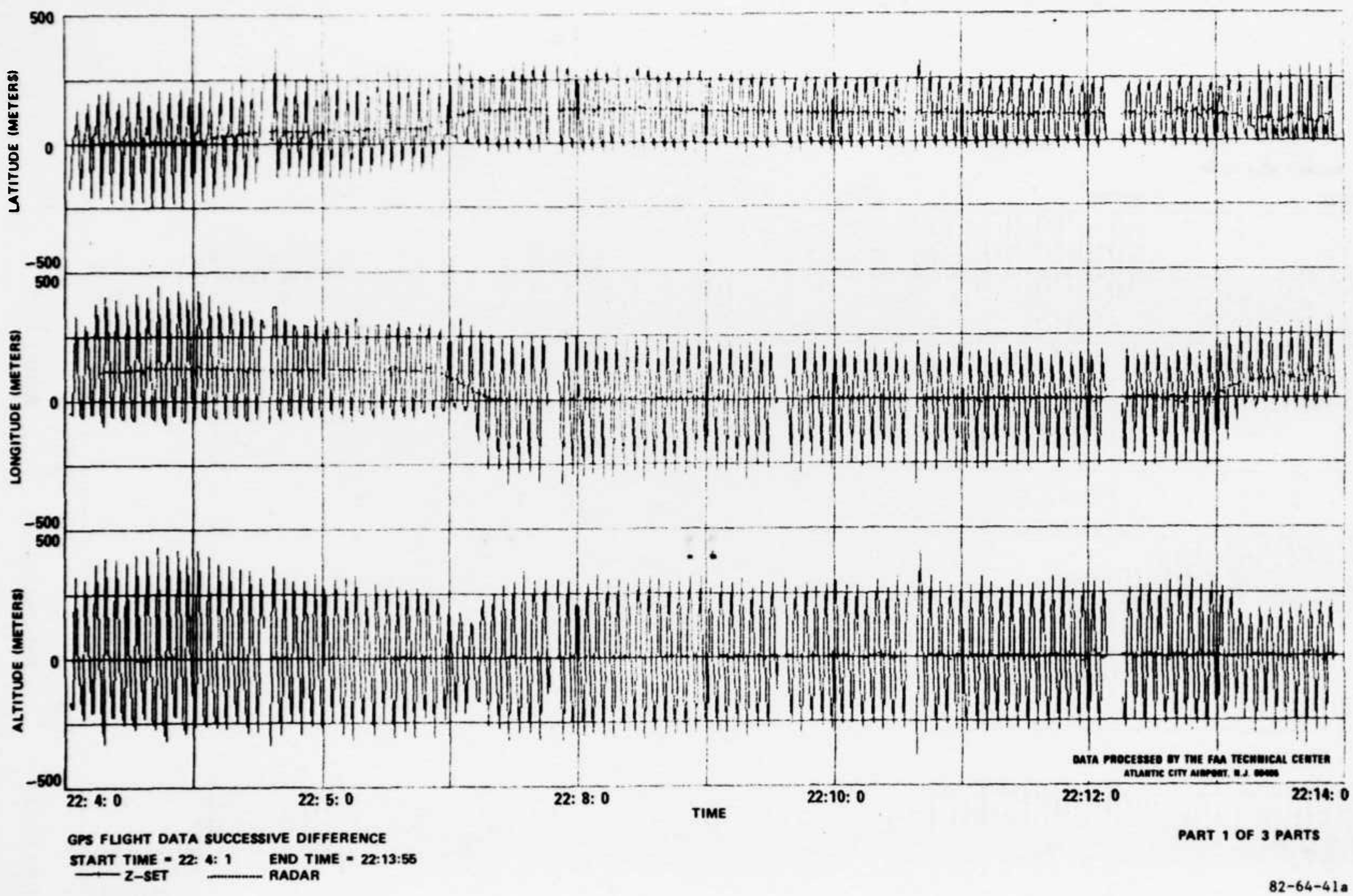

FIGURE 41. SUCCESSIVE DIFFERENCE PLOT FOR JULY 15, 1981, FLIGHT IN CAL MODE (SHEET 1 OF 3)

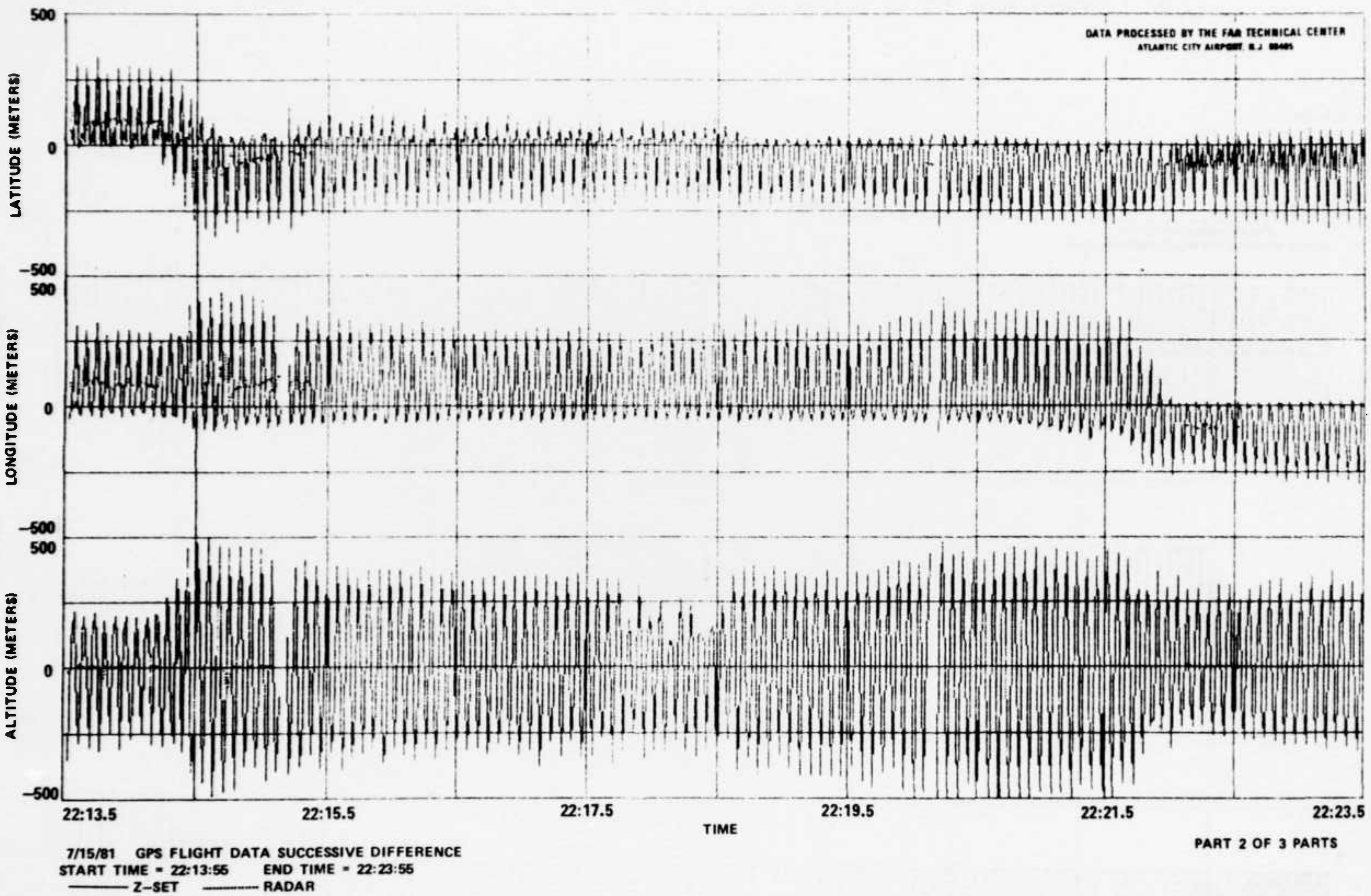

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FIGURE 41. SUCCESSIVE DIFFERENCE PLOT FOR JULY 15, 1981, FLIGHT IN CAL MODE (SHEET 2 OF 3)

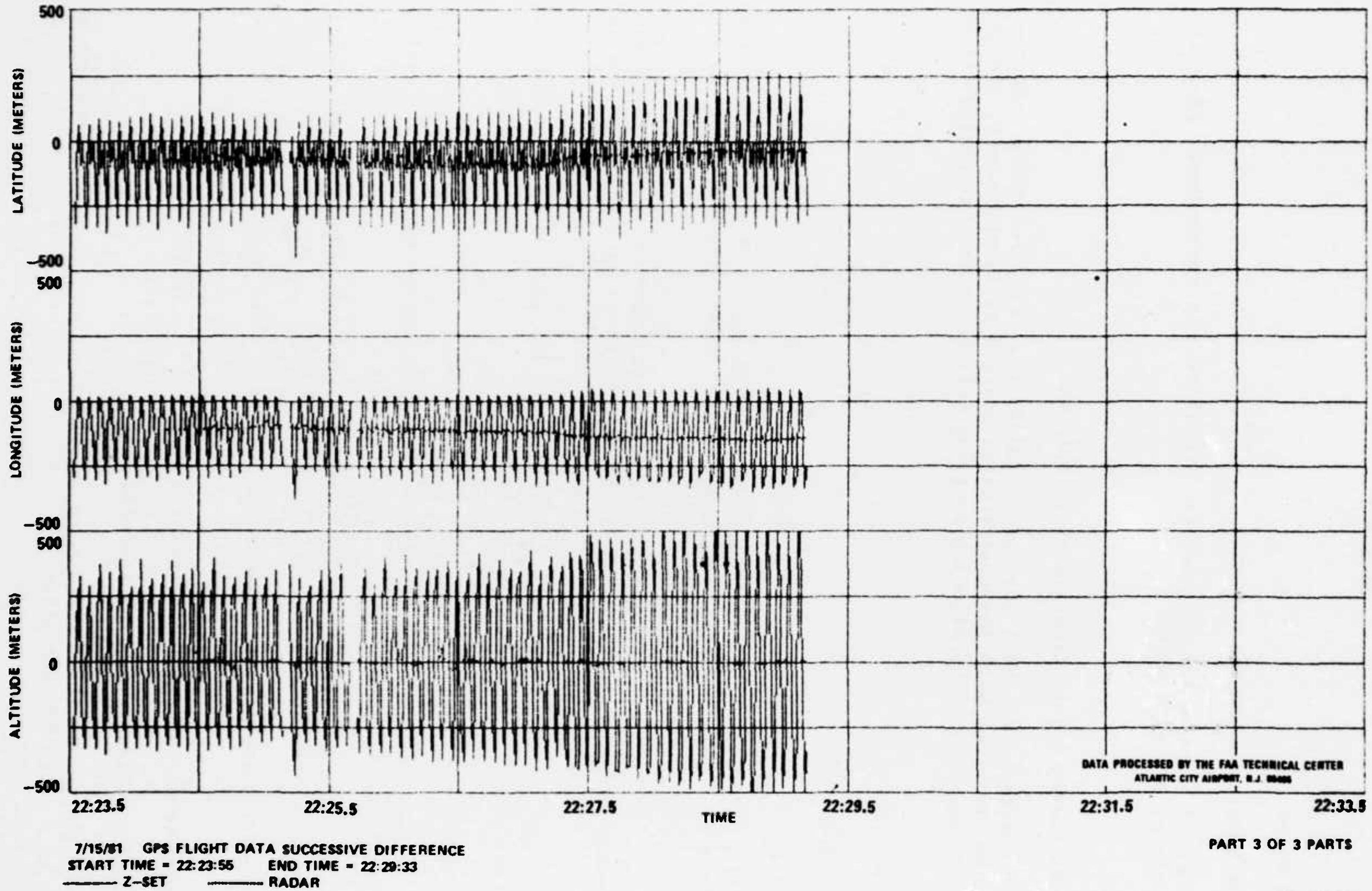

FIGURE 41. SUCCESSIVE DIFFERENCE PLOT FOR JULY 15, 1981, FLIGHT IN CAL MODE (SHEET 3 OF 3)

GLOSSARY

ABS - Absolute value.

AHRS - Altitude heading reference system.

Almanac - A set of data which is used to calculate the approximate position and clock offsets of GPS satellites.

ALT - Altitude.

C/A Signal - GPS coarse acquisition signal at 1575 MHz.

CAL Mode - Calibration mode which accurately calibrates the Z-set clock such that navigation can be performed with three satellites instead of four; however, the set should not be moving because the velocity coupling effects in the navigation filler are deleted.

CDU - Control display unit.

C/I - Control/indicator.

COEF - Correlation coefficient, w, see appendix B.

Delta Mean Plots - Plots of the mean error evaluated every 30 seconds from differences between the Z-set derived position and the known surveyed/radar derived position.

Delta Sigma Plots - Plots of the standard deviation evaluated every 30 seconds from differences between the Z-set derived position and the known surveyed/radar derived position.

DME - Distance measuring equipment providing distance information from the aircraft to the DME transmitter.

DOD - Department of Defense.

DX - Tracker determined position in true north-south direction minus Z-set position where north direction X is positive.

DY - Tracker determined position in east-west direction minus Z-set position where east direction Y is positive.

DZ - Tracker determined altitude minus Z-set altitude where the upward direction Z is positive.

ECEF - Earth-centered earth-fixed coordinates.

EPE - Estimated position error, see appendix B.

Ephemeris - A set of data which is used to calculate the accurate position and clock offset of a given GPS satellite.

EST - Eastern standard time (5 hours behind Greenwich Mean Time).

FAA - Federal Aviation Administration.

FRP - Federal Radionavigation Plan.

GDOP - Geometric dilution of precision, see appendix B.

GMT - Greenwich Mean Time.

GPS - Global Positioning System.

GSPD - Ground speed.

GTK - Ground track.

HDOP - Horizontal dilution of precision, see appendix B.

GVAR - Estimated variance of four-dimensional error, see definition for SQRT GVAR.

ILS - Instrument Landing System providing aircraft with precision vertical and horizontal information during approach and landing.

INIT mode - Z-set initialization mode in which the operator is required to power the unit and enter data prior to the start of the standby mode.

INS - Inertial Navigation System.

LORAN - Long Range Navigation System providing total coverage for U.S. contiguous waters and adjacent land areas.

Mean - Summation of the value divided by the number values, see appendix B.

NAV Mode - Navigation mode for Z-set (i.e., the normal flying mode of the Z-set which occurs when its estimated position error is less than 2 nmi).

NAVSTAR - Navigation System Using Time and Ranging.

OMEGA - A radionavigation system providing nearly world-wide coverage.

Outer-Middle-Inner Marker Beacon - ILS equipment providing information for final approach.

PDOP - Position dilution of precision, see appendix B.

PL - Position localizing interface unit.

RFI - Radiofrequency interference.

Sigma - Standard deviation σ, see appendix B.

SQRT GVAR - The square root of GVAR, or the estimated four-dimensional 1-sigma error (position and time) in meters as determined by the Z-set Kalman filter, whose time error is multiplied by the velocity of light.

Standard Deviation - σ, see appendix B.

Standby Mode - Mode in which the Z-set begins satellite acquisition and data gathering (including almanac collection) which will result in entry into the sequential track navigation mode (NAV mode).

Successive Difference Plots - Plots of the differences between either successive Z-set position determination, usually at 1.2-second intervals, or successive radar position determination.

2D - Two-dimensional horizontal difference between the Z-set derived position and the known surveyed/radar derived position.

3D - Three-dimensional spacial difference between the Z-set derived position and the known surveyed/radar derived position.

UTC - Universal time coordinate corrected for earth rotation.

Variance - σ^2, the square of the standard deviation.

VOR - Very high frequency (VHF) omnidirectional range providing bearing information from the aircraft to the VOR transmitter.

VORTAC - Facility providing distance and azimuth information to an aircraft.

w - Correlation coefficient, see appendix B.

WGS-72 - World geodetic system developed in 1972.

WWVB - Radio station broadcasting standard frequency and time signals.

ZIM - Z-set interface module for attachment of barometric altimeter.

Z-set - Prototype civil aviation GPS receiver.

APPENDIX A

GPS FIXED WING POSITION LOCATING INTERFACE UNIT

The fixed wing position locating (PL) interface unit is a Z-80 microprocessor-based data collection and interface unit. It can function as the central processing component of an instrumentation system for small aircraft where space and power are a premium, or as a part of the GPS fixed wing airborne data collection system for large aircraft. The PL unit is an intelligent peripheral device that accepts data from the following equipment:

- Global Positioning System (GPS) Z-Set
- Time standard
- Ground radar tracking telemetry receiver
- Inertial navigation system (INS)
- Altitude heading reference system (AHRS)
- Loran
- Two very high frequency (VHF) omnidirectional radio range (VOR)/Instrument Landing Systems (ILS)
- Two distance measuring equipments (DME)
- Outer-middle-inner marker beacon
- Digital altimeter
- Selected switch positions

The PL unit formats and time tags the information received from the above airborne equipment into data blocks that occur once a second. The data blocks are synchronized with the airborne time code generator. These data are then recorded on an airborne tape recorder under control of the PL unit on small aircraft. On large aircraft, the blocks of data are transferred to the airborne data instrumentation computer for airborne analysis and recording. The data of systems recorded through the PL unit depends on the aircraft in which the unit is installed. For instance, on large aircraft the GPS set is connected directly to the airborne instrumentation system for airborne analysis and display of data. The INS would connect to the PL interface unit and the data transferred to the airborne instrumentation computer. On small aircraft, all systems would be connected to the PL interface unit and the data transferred to the airborne tape recorder.

In the blocks of data formatted by the PL unit and occuring once every second, there are approximately 300 words of data, which include radar tracking data for every 0.1 second. At the radar site aircraft position, data are time tagged every 0.1 second by the radar center's time code generator, which is synchronized to universal time coordinate (UTC) via radio station WWVB. In the aircraft GPS position, data are time tagged to GPS time at the time of the pseudorange measurement. Prior to June 30, 1981, GPS time, within a few nanoseconds, was 2 seconds ahead of UTC. After June 30, 1981, GPS time, within a few nanoseconds, is 3 seconds ahead of UTC. This time difference in GPS and UTC is utilized to correlate and compare the radar tracking aircraft position data with the GPS derived position data.

The difference between the airborne time standard and the GPS time is recorded on the aircraft instrumentation tape and utilized to correlate and compare GPS position data with the position data of other airborne systems (e.g., the INS).

A block diagram of the PL unit interface is shown in figure A-1; a listing of signal inputs is shown in table A-1.

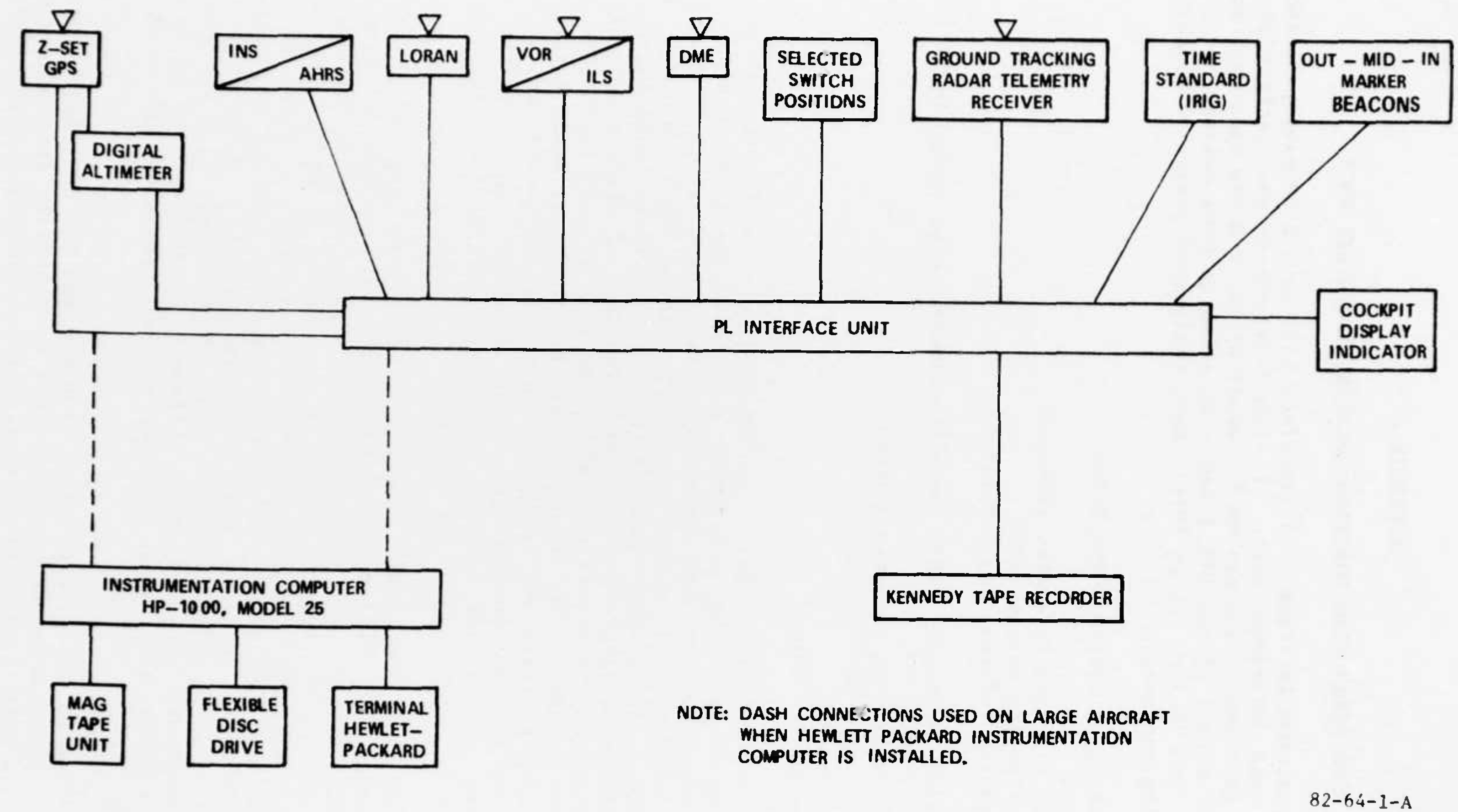

FIGURE A-1. BLOCK DIAGRAM OF PL UNIT INTERFACE

TABLE A-1. PL SIGNAL INPUTS

PL System Inputs

Source	Description	Format	Range Resolution
Time Code Generator		BCD (parallel)	Day/hr/min/sec/0.1 sec
INS	Latitude	Sync. binary (serial)	±180° (0.25°)
	Longitude		±180° (0.25)
	Ground speed		±3276.7 kts (0.1 kt)
	Track angle		0 to 360° (0.64°)
	True heading		0 to 360° (0.64°)
	Wind speed		±3276.7 kts (0.1 kt)
	Wind angle		±180° (0.64°)
	N-S velocity		±3276.7 kts (0.1 kt)
	E-W velocity		±3276.7 kts (0.1 kt)
INS or altitude/ heading reference system	Heading	Synchro/4 wire	0° to 360°
	Pitch	Synchro/4 wire	±90°
	Roll	Synchro/4 wire	±180°
Tracking radar telemetry receiver sample time		Async. binary (serial) 24 bits	(1/32 sec)
	Latitude		$\pm \frac{\pi}{2}$ rad (0.40°)
	Longitude		$\pm \pi$ rad (0.40°)
	Height		(1 ft)
	Range (radar)		(1 meter)
VOR	Radial		0° to 360° (1°)
	Tuning	Digital (2 of 5 codes)	360 channels (50 kHz)
	AGC	Analog d.c.	0 to 2V
DME	Range	Analog 40mV/nmi	0 to 99 nmi (0.1 nmi)
	Speed	Analog 20mV/kt	0 to 500 kts
CDI (VOR/ILS/GPS)	Deviation	Analog d.c.	Full scale (full scale 100)
Altimeter	Altitude	Parallel Binary (gray)	-1,000 to +100,000 ft (100 ft)
Flags	VOR	28V	N/A
	DME	150mV	N/A
	Marker beacon	12V	N/A
	(Inner, middle, outer)		N/A
	VOR/ILS	28V	N/A
	VOR/GPS	28V	N/A

Z-Set - Derived position utilizing earth-centered earth fixed coordinates (ECEF) converted to latitude, longitude, and altitude in WGS-72 coordinate systems.
- Number of each satellite in the constellation selected by the Z-set providing data.
- Number of satellites presently providing data.
- Number of satellites for which ephemeris data has been collected.
- Z-set derived ground speed.
- Z-set derived ground track.
- Z-set dwell counters for each satellite (increased for good data quality, decreased for poor data quality).
- Z-set up-down counters (increased with poor data quality, decreased with good data quality).
- HDOP value for satellite configuration selected.
- GDOP value for satellite configuration selected.
- Estimated position error of the Z-set.
- GPS time in tenths of seconds from the Z-set.

rad = radians

APPENDIX B

MATHEMATICS UTILIZED IN GPS FIXED WING DATA REDUCTION

Equations and assumptions used in computing the single and multidimensional statistical values to analyze the GPS fixed wing and ground monitoring data are listed below for the following parameters.

Means: The bar over the various paramters denotes the respective sample mean value; the subscript i denotes the instantaneous value for the single dimensional variables. The quantity N is the number of observations.

$$\overline{X} = \frac{1}{N} \Sigma_i \; X_i$$

$$\overline{Y} = \frac{1}{N} \Sigma_i \; Y_i$$

$$\overline{Z} = \frac{1}{N} \Sigma_i \; Z_i$$

$$\overline{2D} = \sqrt{(\overline{X})^2 + (\overline{Y})^2}$$

$$\overline{3D} = \sqrt{(\overline{X})^2 + (\overline{Y})^2 + (\overline{Z})^2}$$

Root Mean Square (rms) Values: The quantities $2D_i$ and $3D_i$ are the instantaneous rms values for the two-dimensional and three-demensional cases, respectively.

$$2D_i = \sqrt{X_i^2 + Y_i^2}$$

$$3D_i = \sqrt{X_i^2 + Y_i^2 + Z_i^2}$$

Standard Deviation: The standard deviation is given as σ_k. The distance root mean square (2 drms) is defined as $2\sigma_2$. The 2-drms value for a bivariate normal distribution (in which the X and Y variables are assumed independent and their means zero) refers to the radius of the circle which contains approximately 95 percent of the data points.

$$\sigma_X = \sqrt{\frac{1}{N-1} \Sigma_i \left(X_i^2 - N(\overline{X})^2 \right)}$$

$$\sigma_y = \sqrt{\frac{1}{N-1} \sum_i Y_i^2 - N(Y)^2}$$

$$\sigma_z = \sqrt{\frac{1}{N-1} \sum_i Z_i^2 - N(Z)^2}$$

$$\sigma_2 = \sqrt{\sigma_X^2 + \sigma_Y^2}$$

$$\sigma_3 = \sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2}$$

Correlation Coefficient: The quantity w is the sample correlation coefficient which may vary from -1 through 0 to +1, and is a measure of the linear relationship between the variables x and y. A correlation coefficient of zero does not necessarily indicate that x and y are independent since there may exist a nonlinear association between the variables.

$$w = \frac{\sum_i \left(X_i Y_i - \bar{X}\bar{Y}\right)}{\sqrt{\left[\sum_i (X_i^2 - \bar{X}^2)\right] \left[\sum_i (Y_i^2 - \bar{Y}^2)\right]}}$$

GDOP: The geometric dilution of precision (GDOP) reflects the influence of satellite geometry on the user's estimate (1σ value) of his position (x, y, and z) and his clock offset (time) through the functions of the user-satellite direction cosines. The GDOP deviation assumes that the satellite measurement errors are uncorrelated and have equal standard deviations and zero means (see Milliken and Zoller in reference "e" under Related Documentation).

$$GDOP = \sqrt{a_x^2 + a_y^2 + a_z^2 + a_t^2}$$

PDOP: The quantity PDOP refers to the three-dimension position dilution of precision.

$$PDOP = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

HDOP: The quantity HDOP refers to the two-dimensional horizontal dilution of precision in the xy plane.

$$HDOP = \sqrt{a_x^2 + a_y^2}$$

EPE: The quantity EPE is defined as the estimated three-dimensional 1-signal position error as determined by the Z-set Kalman filter.

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EPE: The quantity EPE is defined as the estimated three-dimensional 1-signal position error as determined by the Z-set Kalman filter.

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